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GEOMORPHIC APPROACH TO REGIONAL SEDIMENT MANAGEMENT IN ENGINEERED AND RESTORED FLUVIAL SYSTEMS

FINAL REPORT

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by

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SUMMARY

This document reviews contemporary practice in regional sediment management. It examines whether catchment wide sediment issues have been considered in the design of engineering and restoration/rehabilitation projects. The study has been undertaken through a review of documented literature in addition to contacting leading practitioners in the field. The results suggest that historically catchment wide sediment issues were rarely addressed in the design of schemes, leading to many project failures. Recently, however, there has been increased consideration of regional sediment issues in the design of schemes. This has been complemented by the development of an increasing number of design approaches that include sediment continuity as an integral part of their procedure. The use of these approaches is still fairly limited and they remain unproven as practical tools. Consequently, there is a need to further refine these methods and ensure that they are suitable to be adopted into widespread engineering practice.

In addition, an important requirement for future practice is to enable schemes to be designed taking into account previously documented experiences. This will help projects avoid previous mistakes and define best practice for the future. As a result, an existing geomorphic Post-Project Appraisal approach has been refined to focus specifically on the assessment of regional sediment issues. A Regional Sediment Appraisal Methodology has thus been developed and outlined here.

Broad conclusions from the project suggest that:

- Historically regional sediment management has been inadequately addressed in the design of projects and this is illustrated by the large amount of failures that have been discovered (Frissell and Nawa, 1992; O'Neill and Fitch, 1992; Beschta *et al.*, 1994; Miles, 1998).

- A number of catchment based approaches evolved during the 1990s. Their main focus has been to develop an understanding of how the watershed and drainage system operates before siting and designing river engineering projects and management schemes.

- The main types of projects that have addressed sediment continuity in their design have either been demonstration projects, large interdisciplinary schemes or those that have had a significant academic involvement. Sediment continuity is seldom addressed routinely in operational projects.

- Monitoring and performance appraisals of schemes are seldom undertaken in flood control projects and are still rare in river restoration programmes.

Key recommendations are:

- Future river management projects need to adopt a watershed approach to enable schemes to be located, and designed, appropriately to ensure sediment continuity is maintained.

- Research should be performed to further test and refine catchment and reach-scale approaches to enable these techniques to be used in the design and siting of restoration projects.

- Present qualitative analyses of watershed and reach-scale should be further developed to provide the basis for quantitative sediment budgeting at the scale of the fluvial system. A central component of this technique should be the ability to define the point where a particular grain size switches from wash load to bed material load within the fluvial system.

- Engineers and river managers should recognise that monitoring and performance appraisal should become standard components of best practice in flood control and restoration since they offer the opportunity to learn from contemporary experience. Not only do the results of monitoring and appraisal underpin adaptive management of schemes but they can be used to develop improved designs.

- The Regional Sediment Appraisal methodology for assessing sediment related issues in restored and engineered fluvial systems presented here should be assessed and refined through consultation with selected operations staff in the US Army Corps of Engineers District offices.

USEFUL WEBSITES

River Restoration Centre, UK -	http://www.aecw.demon.co.uk/rrc/rrc.htm
European Centre for River Restoration, Denmark -	http://www.ecrr.org
Kissimmee River Restoration -	http://www.sfwmd.gov/org/erd/krr/index.html
Federal Interagency Stream Restoration Working Group -	http://www.usda.gov/stream_restoration
Australian River Rehabilitation (Co-operative Research Centre for Catchment Hydrology) -	http://www.catchment.crc.org.au
Demonstration Erosion Control Project (at ERDC) -	http://www.wes.army.mil
Demonstration Erosion Control Project (at Colorado State Univ.) -	http://www.colostate.edu/Orgs/CRSS

KEYWORDS

Applied Geomorphology	Catchment Baseline Survey	Flood Control
Fluvial Audit	Fluvial Hydrosystem	MaintenancePost-
Project Appraisal	Regional Sediment Management	River Restoration
River Styles	Sediment Budget	Stability

1. INTRODUCTION

All fluvial systems are periodically disturbed by the impacts of extreme events such as floods and droughts. In addition, most fluvial systems in developed nations have been significantly altered by human activities. Often, alterations are unintentional and result from changes in watershed land-use and water resource development. However, other alterations are intentional and are performed improve the function of the river with respect to flood control, navigation, water supply, sediment management, irrigation, recreation, hydropower, and mineral extraction. In this regard, dams, levees, diversion structures may be constructed, and the morphology of the river changed through straightening, widening, deepening, and clearing of the channel. Recently, greater emphasis has been placed by society on the value of rivers as natural resources supporting valuable habitats, promoting biodiversity and fulfilling a strong recreational role. As a result, further alterations take place for fish, wildlife habitat and aesthetic improvement. Schemes involving environmental and ecological improvement are intended to enhance the river and yet they too may induce instability unless care is taken to ensure that they perform consistently in the sediment transfer system.

The cumulative impacts of intended and unintended interventions in fluvial systems have significantly disrupted many stream systems and the ecosystems which they host. The disruption of the sediment transfer system, augmented by sediments generated by the schemes themselves, reduces the efficiency of flood control channels, destroys wetlands and lakes, adversely impacts fish and wildlife habitats, degrades water quality of streams, adversely impacts infrastructure, and initiates accelerated stream instabilities.

In the past, river engineering largely concentrated on the construction of single-purpose, structural projects for flood control and navigation. This focus has gradually shifted to the design of river control projects on a system-wide or regional basis, particularly with respect to sediment management. Many projects implemented over the past few years have attempted to address sediment management within a systems context. Ideally, the outcomes of these projects should yield valuable insight and understanding that could guide the designers of future schemes. Unfortunately, the experience gained by project designers and managers tends to be held by the individuals and no corporate knowledge has been built up because post project monitoring has been very limited, or non-existent. In fact, the successes, limitations and performance of most engineering and rehabilitation projects with a regional sediment management component have usually been reported anecdotally. As a consequence, limited design guidance exists for systematic approaches to regional sediment management, both on a national and international basis.

This report outlines contemporary practice in regional sediment management. This is achieved in two ways. Firstly, an extensive examination of documented evidence has been undertaken. A critical review of various journal papers and reports details a number of approaches that are used to regionally manage sediment throughout the world. The second part of the study reviews information gleaned from various practitioners in the field. Combined these sources have provided sufficient documentation to construct a clearer picture of current practices relating to regional sediment management.

Ideally reliable, accurate evidence and experience from existing schemes should form the basis for avoiding the mistakes of the past and defining best practice for the future. However, to

meet the needs of the engineering community, collection of evidence and experience must be based on a rigorous and repeatable methodology. In this regard this report furthers the development of a post-project appraisal procedure (Skinner, 1999) that specifically focuses on the assessment in the context of regional sediment management. The appraisal procedure presented here has been adapted from an earlier version recently developed at the University of Nottingham for the UK Environment Agency.

2 REGIONAL SEDIMENT MANAGEMENT- DOCUMENTED EVIDENCE OF CURRENT PRACTICE

2.1 Approaches to watershed sediment management

2.1.1 Traditional Approaches to sediment management

Sediment related problems have been identified as a major cost in river management for a number of years. In the England and Wales alone it has been suggested that sediment related maintenance costs the Environment Agency in excess of $16 million per year (Environment Agency, 1998a). The maintenance procedures are therefore expensive and can broadly be split into two main areas:

a) planned preventative maintenance;
b) breakdown maintenance.

There are a number of problems with these approaches. Planned maintenance may not be required and hence operators run the risk of spending resources unnecessarily, while breakdown maintenance treats local erosion and siltation problems in isolation from channel form and process at the watershed scale (Sear *et al.*, 1995). It is this focus on the local scale that has been identified as a major problem with historic sediment management in rivers. By neglecting watershed scale processes in the design of schemes, sustainable river sediment management has rarely been practiced. There remains a large emphasis on routine sediment maintenance and 'desilting' in many engineered channels that fails to address the causes of siltation and that takes place with no knowledge of the source of the sediment. Such maintenance is seldom cost-effective, has adverse environmental impacts and is not sustainable.

Ideally, the emergence of 'designing with nature' (McHarg, 1969) in river management should have led to the development of more sustainable approaches to channel design and maintenance. However, several recent large-scale studies have highlighted a high degree of design failures amongst river restoration schemes (Frissell and Nawa, 1992; O'Neill and Fitch, 1992; Beschta *et al.*, 1994; Miles, 1998). A review by Miles (1998; Table 1) of schemes in the Northwest USA and Canada suggests that the highest physical success rate for a variety of projects was 82% whilst the lowest was only 40%. Miles (1998) also undertook a more detailed examination of specific success rates on the Coquihalla and Coldwater rivers in Southwest British Columbia following a flood with a 35-40 year return period. He found that 41% of all structures on the higher energy Coquihalla River and 5% on the Coldwater River were either washed away, buried or no longer present within the low water channel following this flood. In addition, 87% of all structures on the Coquihalla and 78% on the Coldwater lost approximately 50% of the structural material that had been used in their construction. Frissell

and Nawa (1992) in their study in Washington and Oregon discovered similar levels of project failure. They found that the most common causes of damage were the deposition of bedload in wide, low-gradient alluvial valley reaches and the erosion of streambanks and shifting channels associated with this deposition.

High rates of failure in contemporary practice have led some authors (Beschta *et al.*, 1994) to question whether it is wise to continue to spend resources on schemes that fulfil short-term objectives whilst falling short of longer-term requirements of sustainable channel stabilisation or rehabilitation. For example, a sustainable long-term goal in a restoration scheme would be to re-establish fluvial processes that form fisheries habitats rather taking the short-term fix of artificially creating habitats using engineered structures (Miles, 1998). The long-term approach can only be undertaken through proper stewardship of the river and its watershed (Beschta *et al.*, 1994) based on understanding the site's wider spatial and temporal context. This is particularly relevant with respect to the geomorphic processes and adjustments (Kondolf and Downs, 1996) that drive the regional sediment dynamics of the system.

Table 1: Measured physical success rates of various fisheries restoration schemes

Project Location	Success rate
Washington and Oregon	40%
Alaska	44%
British Columbia	55%
Southwestern Alberta	62%
US National Forests	80%
Oldman River dam, Alberta	82%

(adapted from Miles, 1998)

2.1.2 Watershed approaches to sediment management

The starting point for any regional sediment management project must be a sound understanding of the fluvial system. As Sear (1996) argues there is no point in trying to construct a stable channel in the project reach if the sediment input from the adjacent upstream reach is about to become unstable because it is approaching a threshold condition for channel change. By understanding that the project reach is not isolated, but is integrally connected to the sediment system continuum (Sear, 1994) the chances of success for a scheme will be significantly increased. There have been numerous advocates of such an approach in recent years in North America, Europe and Australia (Sear *et al.*, 1995; Kondolf and Downs, 1996; Petts and Amoros, 1996a; Environment Agency, 1998b; Harper *et al.*, 1999; Brierley and Fryirs, 2000). However, developing techniques that are capable of accurately identifying current and potential sediment sources, pathways and storage locations at a variety of scales within the watershed and its drainage network is a major challenge. Sediment sources may stem from localised erosion, that can be assessed using simple analyses and conventional bed and bank stabilisation techniques, to severe, basin-wide problems that require sophisticated analyses and design efforts involving the entire watershed and fluvial system. A brief review of some of the recent watershed based approaches that have evolved is made below.

River Geomorphology : A Practical Guide (adapted from Environment Agency, 1998b)

In 1998 the UK Environment Agency produced a Guidance Note titled 'River Geomorphology: A Practical Guide.' This document includes a suite of approaches that could be used for applying system-analysis to river management. The procedures are outlined below:

Watershed Baseline Survey

A watershed baseline survey is used to provide a strategic assessment of the geomorphological 'state' of the river. There are two levels to this survey. The first is a broad desk study of geology, soils, topography, land-use and geomorphology within the watershed to determine the characteristics of the watershed. The second level is a more detailed assessment of the character of the channel. The data collected in the survey are used to sub-divide the channel network into lengths that possess similar morphological characteristics. This information can be, for example, combined with the desk study to define the geomorphological conservation value of each reach. This scheme classifies reaches by their susceptibility to disturbance rating them on a gradient from High to Low with additional categories for channelised, culverted and navigable channels. The information collected can be used to help determine the extent to which the channel is stable, modified or recovering towards a natural state from a previously modified form.

Example (see section 2.2.3 for more details on the River Idle channel rehabilitation project):

Downs, P.W. and Thorne, C.R., 1998, Design principles and suitability testing for rehabilitation in a flood defence channel: the River Idle, Nottinghamshire, UK, *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**, 17-38.

Fluvial Audit

A fluvial audit develops a qualitative assessment of the sediment budget in a previously identified problem reach within the context of the wider watershed system. The audit uses the results of the watershed baseline survey to focus in on problem reaches. In the absence of a full baseline survey the fluvial audit can be extended to form a stand-alone procedure.

Two important sources of information are used within the fluvial audit. Firstly, archival information is used to estimate times and rates of channel change; identify nature and timing of land use changes; identify changes in river management practices. Secondly, a field survey is used to assess the character of the reach in particular to determine any Potentially Destablising Phenomena together with an identification of indicators of channel instability/stability and historic channel change (Sear *et al.*, 1995).

Three outputs of a fluvial audit are:

- Time chart of watershed changes that may have impacted the fluvial geomorphology;
- A map indicating the watershed features important to the fluvial geomorphological character of the channel;

- A detailed geomorphological map of the channel within and adjacent to the problem reach.

(Environment Agency, 1998b, p16)

For further information see:

Sear, D.A., Newson, M.D. and Brookes, A., 1995, Sediment-related river maintenance: the role of fluvial morphology, *Earth Surface Processes and Landforms*, **20**, 629-647.

Geomorphic Dynamics Assessment

A Geomorphic Dynamics Assessment forms the most intensive system study methodology. This requires a quantitative analysis of a particular problem at a reach scale or smaller assessing the morphology, geomorphological processes, process-form links and sensitivity to change. These techniques are largely at a research level but two of the most commonly used are a quantitative assessment of hydraulic geometry and a detailed reconnaissance survey for streambank assessments.

Geomorphic Post-Project Appraisal

A Geomorphic Post-Project Appraisal forms the major post-installation procedure. This is often a neglected part of the process but should be considered as an integral stage since without this there is no method for learning from the results of previous projects. The developed PPA procedure (see Skinner, 1999 for more details) uses a desk study, reconnaissance survey, a compliance audit, performance audit and geomorphic evaluation to assess a project. The main assessment sections of the procedure uses a compliance audit to determine whether the scheme was installed as planned and a performance audit to evaluate the temporal and spatial success of the project. The results are brought together in the geomorphic evaluation to assess short-term objectives and likely longer-term sustainability of the scheme.

For further information see:

Environment Agency, *in press*, Geomorphological Post-Project Appraisals of River Rehabilitation schemes, by Downs P.W. and Skinner, K.S.

Skinner, K.S., 1999, Geomorphological Post-Project Appraisal of river rehabilitation schemes in England, Unpublished PhD thesis, University of Nottingham, Nottingham, UK.

River Styles a Geomorphic approach to watershed characterization (adapted from Brierley and Fryirs, 2000)

Brierley and Fryirs (2000) outline a geomorphic approach for analysing the interactions in biophysical processes within a watershed scale context. An essential underlying tenet behind the development of this framework is that geomorphic processes define the physical template of a river system upon which the interaction of a wide range of biophysical processes occurs. This interrelationship leads to the evolution of distinct units within different parts of the watershed. Brierley and Fryirs (2000) form a hierarchical approach to river chacterization from

the watershed scale/sub-watershed level through landscape units, river styles and to the smallest scale geomorphic units (Figure 1).

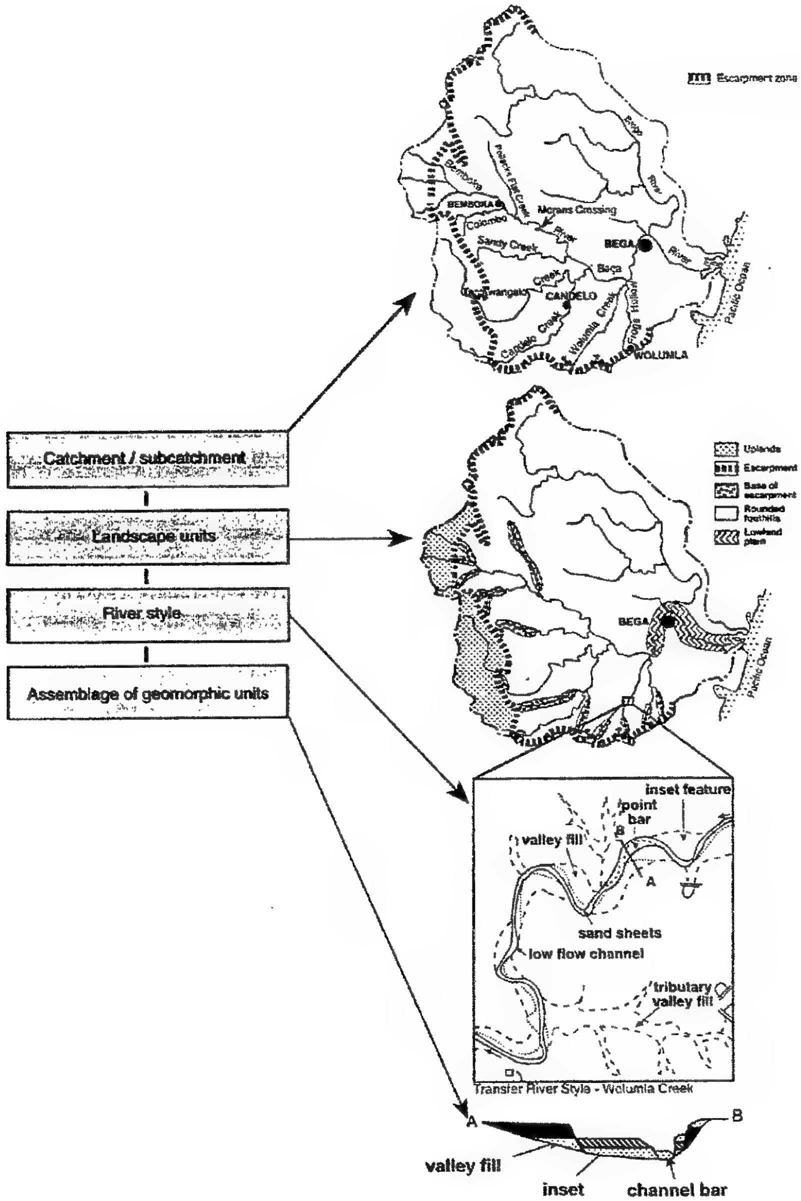


Figure 1: Illustration of the River Styles Approach (from Brierley and Fryirs, 2000, p663)

A key feature behind the approach developed by Brierley and Fryirs (2000) is the need for it to be flexible so that it can be used to explain river behavior in both spatial and temporal contexts. It is necessary to understand how a river channel has changed over time in the watershed rather than just being able to classify the reach by virtue of particular features. In the River Style approach the various different units are used to describe features at a variety of scales. The landscape units represent characteristic landforms patterns and are differentiated by virtue of their physiographic setting and morphology. Within each landscape unit there is a series of river styles. Brierley and Fryirs (2000, p662) describe river styles as "river reaches that have a

characteristic river structure analysed in terms of hydraulic geometry (size and shape), channel planform, and the assemblage of geomorphic units in a river reach." These features represent distinct interactions between morphology and the processes that create this form.

Historically, in Australia rehabilitation projects have frequently been implemented in a piecemeal approach, in isolation from their wider watershed scale context (Brierley and Fryirs, 2000). Through using the river style methodology it should be possible to target rehabilitation in reaches which exhibit a stable character and behavior with respect to the water and sediment budgets. Through setting rehabilitation in this context it should be possible to increase the chances of successful projects. The River Style methodology thus offers an alternative strategic watershed based approach for co-ordinating sustainable restoration attempts.

Fluvial Hydrosystem Concept (adapted from Petts and Amoros, 1996a)

A similar approach to the River Styles methodology developed in Europe is the Fluvial Hydrosystems Concept (Petts and Amoros, 1996a). This concept views the watershed as a four dimensional system comprising of the whole river corridor encompassing the river channel, riparian zone, floodplain and alluvial aquifer. The fluvial system is not only affected by longstream processes but also by lateral and vertical fluxes, and strong temporal changes (Petts and Maddock, 1994). Like the river styles approach an important underlying principle of the fluvial hydrosystem is that the interactions between the fundamental hydrological and geomorphological processes determine the types of habitats present along with the strength, duration and frequency of their connectivity (Petts and Amoros, 1996b).

In the fluvial hydrosystems approach it was recognised that complex histories of river basins means that a simple continuum from source to mouth does not, in practice, exist but instead there are a series of functional sectors. Differences between these sectors relate to contrasting process regimes, such as the channel form, flow, sediment transport and temperature, and the different types of habitat and their relative stability over time (Petts and Amoros, 1996c). Within these functional sectors a number of smaller scale functional sets exist. These possess typical ecological units that are associated with specific landforms, such as a meander (Petts and Amoros, 1996c). The functional sets are less persistent than the functional sectors and tend to last between 10^1 and 10^3 years on a large river, such as the Upper Rhone (Petts and Amoros, 1996c). At increasingly smaller scales are functional units characterised by a typical plant or animal community and indicative of particular habitat conditions that exist at a site (Petts and Amoros, 1996c). The individual functional units tend to be arranged in spatial successions along topographic gradients and evolve from a single origin through progressive changes over periods of 10^{-1} to 10^2 years (Petts and Amoros, 1996c). The final subsystem is the meso-habitat such as a gravel patch or sand bar. These are particularly sensitive to variations in the surrounding conditions and thus appropriate time scales for their analysis range approximately from 10^{-2} to 10^1 years (Petts and Amoros, 1996c).

The five different levels (drainage basin, functional sector, functional set, functional unit, mesohabitat) provide the basis for the fluvial hydrosystem approach. A key characteristic is the different degree of persistence of each level ranging from the drainage basin down to the mesohabitat.

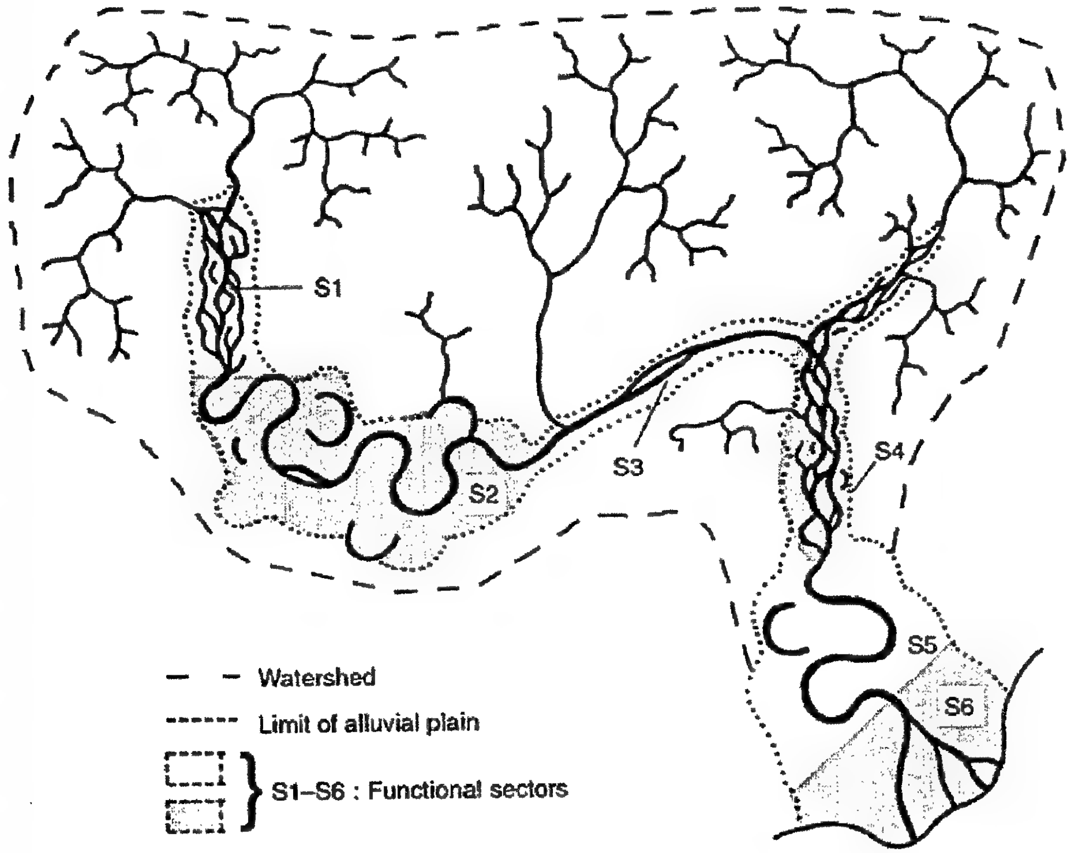


Figure 2: Illustration of functional sectors within the Fluvial Hydrosystem Approach (from Petts and Amoros, 1996, p8)

There are numerous complex interactions between the hydrology, geomorphology and ecology at each of the scales outlined above (see Petts and Amoros, 1996a, for further details). The general structure of the fluvial hydrosystem reflects the interactions between these fluvial and biological processes over a range of time-scales (Petts and Amoros, 1996c). Of particular importance, especially in recent years, is the need to understand how anthropogenic impacts have also impacted the system as a whole. For successful rehabilitation, schemes must address various elements of the fluvial hydrosystem approach. These include:

- watershed scale issues with respect to flows and sediment loads;
- local (sector scale) issues with regard to channel dynamics, especially erosion and deposition;

(Petts and Amoros, 1996b)

The fluvial hydrosystem concept thus offers a holistic approach to the understanding of river systems. The developed watershed scale approach offers a framework within which sustainable rehabilitation schemes could be set.

2.1.3 Detailed approaches to river design

The watershed based approaches outlined briefly in 2.1.2 focus on improving the understanding of the watershed system. Through performing a thorough watershed based assessment of connectivity and continuity in the sediment system, the wider context for a flood control or restoration scheme may be established. A basin-wide survey is an essential component of any design procedure and should be undertaken to guide the identification of off-site issues and impacts when performing feasibility studies and setting preliminary design objectives for any project. However, watershed surveys do not provide a basis for detailed design. Further methodologies are required to determine a suitable design at a reach scale. The design approach adopted must build on the understanding of the sediment system within which the scheme must operate by ensuring that sediment continuity is satisfied in the post-project channel. Such an approach to channel design for restored rivers has been developed by Soar (2000) at the University of Nottingham, UK. This is outlined in more detail below to provide an example of an emerging design methodology for channel design that employs engineering-geomorphic principles designed to be consistent with sound regional sediment management.

Channel Restoration Design for Meandering Rivers (adapted from Soar, 2000)

Soar (2000) recognises the need to maintain or re-establish a balance between the sediment supply and the available transport capacity within the project reach to ensure that sediment continuity is maintained. The approach recognises that, ultimately, the river is the best restorer of itself with respect to intricate cross-sectional detail and intra-reach morphological features. This is allowed for in the framework by designing a general channel mould to generate broad channel dimensions which will then 'prompt' the river to recover a more detailed channel morphology. The channel restoration framework emphasises the need to view the restored reach as part of a connected sediment continuum. To ensure this continuum is maintained the designer needs to consider the imposed upstream (supply) and the downstream (demand) reaches (Figure 3) as essential components in the design of the restored reach.

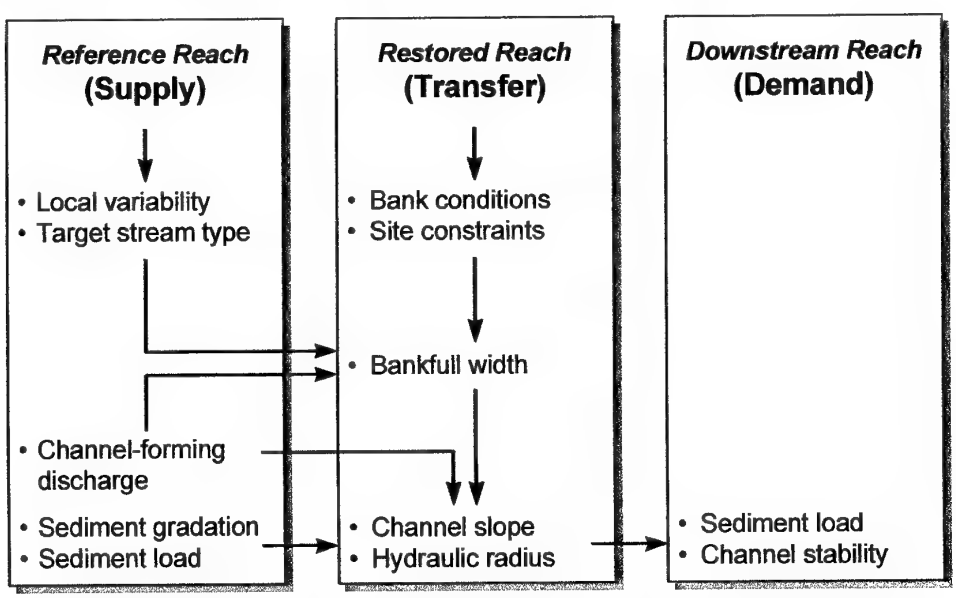


Figure 3 : Sediment Continuity in the fluvial system (from Soar *et al.*, 2001)

The design framework is structured into four stages:

1. Supply Reach Assessment
2. Project Reach Assessment
3. Channel Design
4. Final Design Brief

Supply Reach Assessment

This assessment should follow a thorough watershed baseline study that identified reference reaches and potential stability problems in the watershed. This baseline data should be used to determine the magnitude and frequency of sediment-transporting flow events and a channel forming discharge that would be suitable for defining broad channel dimensions.

Project Reach Assessment

An essential component of the project reach assessment is to determine the available right-of-way (land take) required for the project. In addition it is necessary to identify any form of site constraints at this stage, such as floodplain constrictions, existing structures or the consideration of other project objectives. This information can then be utilised to target the channel type with respect to boundary materials, riparian vegetation and meander pattern.

Channel Design

There are three stages in the design of a stable geometry for the restored river:

- "Determine the reach average dimensions and layout (bankfull width, bankfull depth, bed slope, sinuosity, wavelength and meander path;
- Design local morphological variability around meander bendways (including variable width, location of pools and riffles, maximum scour depth in pools and adjustments to the layout to account for natural variability and site constraints);
- Fine-tune the initial design, based on a channel stability assessment that matches reach sediment transport capacity to the supply from upstream."

(Soar, 2000, p139-140)

Final Design Brief

It is important that the final stage of the design framework is the development of a design brief. This should comprise of computer engineered drawings of various features in a Computer Aided Design (CAD) system. This tool is necessary so that the design drawings are comprehensible to on-site engineers and contractors. This documentation will reduce the chances of elements of the scheme being installed in incorrect locations.

Further Reading:

Soar, P. J., 2000, Channel Restoration Design for Meandering Rivers. Unpublished PhD Thesis, School of Geography, University of Nottingham, Nottingham, UK, 409 pp.

Soar, P.J., Copeland, R. and Thorne, C.R., 2001, Channel restoration design for meandering rivers, Proceedings of the Seventh Federal Interagency Sedimentation Conference, Reno, USA, Volume II, 152-159.

Federal Interagency Stream Restoration Working Group (FISRWG) - Stream Corridor Restoration, Principles, Processes and Practices

The Federal Interagency Stream Restoration Working Group produced a substantial document in 1998 outlining the principles, processes and practices in Stream Corridor Restoration. The Group was multi-disciplinary including 15 Federal Agencies and their respective partners. This review will concentrate on the detailed approaches that are offered for river restoration design specifically focusing on techniques that can be used to estimate sediment transport.

In the Stream Channel Restoration section (8-28 to 8-60) five procedures are recommended to be followed for the design of a new channel. These are:

1. "Describe physical aspects of the watershed and characterize its hydrologic response.

2. Considering reach and associated constraints, select a preliminary right-of-way for the restored stream channel corridor and compute the valley length and valley slope.

3. Determine the approximate bed material size distribution for the new channel.

4. Conduct a hydrologic and hydraulic analysis to select a design discharge or range of discharges.

5. Predict stable planform type (straight, meandering, or braided)."

(FISRWG, 1998, p8-28 to 8-30)

After completion of these steps there are a number of different paths that can be followed. FISRWG manual outlines three example approaches, including one from Hey (1994) and Fogg (1995). The approaches are quite similar and include undertaking various tasks such as:

- determining the meander geometry and its alignment;
- calculate sinuosity and channel length;
- compute mean flow, depth, width and slope at design discharge;
- estimate riffle spacing;
- run a check on channel stability;
- compute flow resistance at design discharge;
- determine bed material discharge;
- calculate boundary shear stress or velocity at design discharge.

(adapted from FISRWG, 1998)

Each of these tasks are examined in more detail in the FISRWG document (p8-28 to 8-30) examining, in particular, the various techniques that can be used to achieve these tasks. It is important to note that all of the outlined techniques will not be applicable to all situations so it is important to select an appropriate suite of techniques when designing a restoration scheme.

Sediment yield and delivery is addressed in several sections in the restoration section (8-53 to 8-60) outlining sediment transport, sediment discharge functions, sediment budgets and sediment discharge, post-design. The sediment transport section deals directly with methods that can be used to provide an estimate of sediment-transport capacity which allows a quick check to see whether deposition is likely to be a problem (FISRWG, 1998). A limitation of the sediment transport relationships is that they are very dependent upon the data that was used to develop them and thus will not be applicable in a variety of situations (FISRWG, 1998). To reduce this error FISRWG (1998) recommend that the most appropriate sediment transport function is selected for the stream type and bed sediment size in question and to calibrate the original relationship with more data. The section reviews several procedures such as SAM (Copeland, 1994) and HEC-6 (USACE, 1993) that can be used to provide an estimate of sediment discharge. However, limitations of these models are that they are based on examining sediment load through straight channels and are not capable of looking at changes either in channel width or planform (FISRWG, 1998). Other models such as GSTARS 2.0 (Yang *et al.*, 1998) are more capable in examining 2/3 dimensional behavior and thus can be used to simulate changes in channel geometry (FISRWG, 1998).

There are numerous sediment discharge functions developed for a variety of different scenarios. It has been recommended that the selection of the sediment transport formula should consider:

- "Type of field data available or measurable within, time, budget, and work hour limitations.
- Independent variables that can be determined from available data.
- Limitations of formulas versus field conditions."

(FISRWG, 1998, p8-55, adapted from Yang, 1996)

FISRWG (1998) recommend 8 different formulas that can be used in the absence of empirical measurements for sediment discharge. Each of these have specific conditions for their use. For example, the Meyer-Peter and Muller equation (1948) should only be used when bed material is coarser than 5mm. If empirical sediment discharge data exists it may be possible to develop a sediment discharge curve, if discharge data is present, to verify sediment discharge relationships.

Sediment budgets can be developed to assess sediment production within the watershed. Various methods, such as measured values, estimates based from similar watersheds or modelling results can be used to estimate a sediment budget for a watershed (FISRWG, 1998). Typically a calculation of the total sediment input from various sources is multiplied by a sediment delivery ratio to give a broad approximation of the amount of soil entering the system (FISRWG, 1998). This is then routed through the system identifying major sinks and transfer zones. It is important that these calculations are calibrated with real data to assess the validity

of the sediment budget model.

Following the implementation of the restoration scheme it is necessary to re-assess the sediment discharge and sediment budget calculations to evaluate whether the system is behaving as anticipated (FISRWG, 1998). If not, then the model should be further validated and used to predict any future changes that might occur within the system.

While neither the hydraulic analysis and engineering design guidance in the manual are state-of-art, it nonetheless provides a valuable example of the wider range of analyses and approaches that can be employed to address regional sediment management during river restoration.

Further reading: Federal Interagency Stream Restoration Working Group (FISRWG) (1998). *Stream Corridor Restoration: principles, processes and practices.* United States National Engineering Handbook, Part 653, Washington, USA, 8-28 to 8-60.

2.1.4 Summary

A series of techniques have been developed in recent years that focus on the need to achieve an understanding of the watershed sediment system before the performing detailed design of flood control and river restoration projects. To be successful the designers need to ensure that longer-term trends of sediment delivery to the design reach and an appreciation of the morphology associated with these loads are considered at a feasibility stage in the project design (Sear, 1996). A sustainable design must be able to accommodate subsequent changes in channel hydrology and sediment yield with minimal intervention in the system. In the next section a review of available literature is presented to assess the degree to which the principles of analysis and design identified in this section have been applied in practice.

2.2 Assessment of documented engineered and restored river schemes

A review of available literature on the design of flood control and river restoration schemes suggests that historically little attention has been given to the larger watershed scale processes. Early documented improvement devices were designed and installed with a project reach emphasis with little consideration of the likely sediment transport through the rehabilitated reach. However encouragingly, larger scale watershed processes are increasingly considered, or at least recognised, in the design of schemes (Sear *et al.*, 1998; Krovang *et al.*, 1998; Toth, 1996; Brookes, 1996). An outline of the various documented approaches is provided in 2.2.1-2.2.5.

2.2.1 Demonstration Projects

Rivers Brede, Cole and Skerne

In 1994 a collaborative effort began in Denmark and the UK to restore 3 degraded reaches of river (Holmes and Nielsen, 1998). The projects on the River Brede (Denmark), Cole (England) and Skerne (England) were supported by European Union 'Life' funds and the country's various statutory bodies (see Biggs *et al.*, 1998; Friberg *et al.*, 1998; Holmes and

Nielsen, 1998; Kronvang *et al.*, 1998; Nielsen, 1996a; Sear *et al.*, 1998; Vivash *et al.*, 1998). The key aims of the project were:

- "to establish a European Demonstration Project applying new state of the art techniques to the restoration of damaged rivers and floodplains;
- to demonstrate the benefits of river restoration for Integrated Watershed Management viz. water quality, river hydrology, flood prevention, nature conservation and amenity etc through a detailed monitoring programme;
- to involve, motivate and train those who influence, or undertake, river management;
- to illustrate how to put partnerships together to facilitate achievement of common goals that cannot be achieved by single agencies alone;
- to determine the costs and benefits of restoration works and disseminate information about river restoration."

(Holmes and Nielsen, 1998)

An important component of the overall project was to ensure that best practice was adopted throughout. Initially this meant that a comprehensive baseline survey would be required on a variety of key parameters (Vivash *et al.*, 1998). In the design of each of the schemes specialists with key expertise were used. These included experts in hydraulic modelling, geomorphology, landscape architecture, fisheries, riparian and aquatic ecology and soil science (Vivash *et al.*, 1998). In the design phase of the scheme a series of design targets and various constraints were developed for each of the three sites. The output of the design process was conceptual 'Visual Plan' that broadly determined the extent and nature of river restoration works for each site (Vivash *et al.*, 1998).

A major component of each of the schemes was the setting up of a comprehensive monitoring programme. This was used to examine various parameter, in particular, physical changes in the channels (considering both sediment movement and hydrology), water chemistry, plant communities, macroinvertebrate communities, fish ecology, landscape change and improvement (Nielsen, 1996a). With regard to hydromorphological considerations, particular attention was given to the effects of re-meandering of the channel on flood levels, floodplain inundation, adjustment in channel morphology, sediment transport and overbank sediment deposition (Kronvang *et al.*, 1998). The hydrogeomorphological effects of the restoration projects are detailed in general in Kronvang *et al.* (1998) and in detail for the River Cole in Sear *et al.* (1998).

Sediment Surveys (adapted from Kronvang et al., 1998; Sear et al., 1998)

On the Brede restoration scheme (Kronvang *et al.*, 1998) the level of sedimentation on the floodplain was measured using a series of cylindrical traps. Twelve to fifteen cylinders were installed at three transects, which represented the up, middle and downstream sections of the project reach. The average deposition was interpolated between each sampling site. Deposition was measured at five periods during the winter of 1994/95 which revealed that average sedimentation rates were correlated with flooding frequency at the upstream section of reach but not in the middle and lower sections. This was thought to be caused partly as a

result of a northern side branch of the channel was acting at a sediment sink in the first winter as a consequence of problems in finishing restoration work. A crude, gross estimate of sedimentation on the floodplain was 189 tonnes over the first winter.

On the River Cole (Sear *et al.*, 1998) a crude sediment budget was undertaken that used both the mean daily flow and sediment records and extrapolated these over the duration of the record using standards flow duration curve methods. These suggested that there was a net loss of suspended sediments from the restored reach leading to the exposure of bare surfaces.

Geomorphic surveys (Kronvang et al., 1998; Sear et al., 1998).

Detailed geomorphic surveys were made on both the River Cole and the Brede. On the Cole these focused on detailed cross-sectional surveys at 3-6 month intervals. On the Brede these were measured every 100m both prior to restoration and immediately following installation. In addition, at two 200m sub-reaches detailed measurements were made every 10m. The detailed surveys enabled an assessment to be made on rates of channel adjustment as well as identifying the location and frequency of geomorphological features. This was further enhanced by the use of a fluvial audit (Sear *et al.*, 1995; EA, 1998) pre and post installation on the River Cole.

Results suggested that on the Brede restoration led to an increase in channel sinuosity, and channel width at bankfull discharge, along with a decrease in channel depth at bankfull discharge and channel slope. The River Cole was characterised by a large increase in channel sinuosity, a general decrease in channel width and depth at bankfull discharge. Following restoration, and a bankfull flow subsequent to installation, the amount of erosional features increased along with the numbers of bars and riffles. These are continuing to evolve as a consequence of the sediment releases. An important feature identified in the Cole monitoring survey has been the development of an aggradational zone in the impacted reach downstream of the restored reach. This is being monitored through repeat surveys, sediment analysis and through photographic evidence. It is important to monitor this zone since a phase of incision could follow this aggradational phase. This could lead to potential stability problems within the project reach.

River Channel Hydraulics and flooding

For the River Brede the Mike-11, 1-d hydrodynamic model developed by the Danish Hydraulics Institute was used to investigate the existing and planned river channel morphology and its hydraulics. In the Cole and the Skerne numerical models were developed to investigate the flooding regime through the HR Wallingford, SALMON F package. The flooding characteristics for each of the three rivers showed a decrease in bankfull flow that will lead to the floodplain being inundated more frequently by the river (see Table 2). Modelling showed that during a 1:100 year flood on the Cole and Skerne there is a dramatic increase is storage capacity on the floodplain thus providing an important flood retention area. In addition, the residence time of the water on the floodplain has increased on the Cole from 19 hours to 32 hours after restoration. This has significant ecological implications for the floodplain habitat.

Table 2: Flooding characteristics of the River Brede, Cole and Skerne pre and post restoration (Figures from Kronvang *et al.*, 1998)

	River		
	Brede	Cole	Skerne
Pre-restoration bankfull discharge	20 m^3s^{-1}	22 m^3s^{-1}	12 m^3s^{-1}
Post-restoration bankfull discharge	7.9 m^3s^{-1}	13 m^3s^{-1}	8.5 m^3s^{-1}
Pre-restoration volume of water on a floodplain during a 1:100 year flood	Unknown	$2.3x10^6m^3$	$3.7x10^6m^3$
Post-restoration volume of water on a floodplain during a 1:100 year flood	Unknown	$3.9x10^6m^3$	$4.7x10^6m^3$

Summary

The demonstration sites on the Rivers Brede, Cole and Skerne have provided a large amount of information on the modelling, installation and post-implementation performance of river restoration schemes. Through dissemination of these results (briefly outlined here) some of the best-practice techniques can be made available to a wide range of practitioners. Through using simple cross sectional analysis combined with a fluvial audit of the reach on the Cole has proved to be an effective method at providing an assessment of the sediment dynamics of the reach post-restoration. Despite the use of a geomorphologist in post-installation monitoring of the Cole the design of the scheme was largely driven by hydraulic considerations and the need to obtain ecological diversity (Sear *et al.*, 1998). Geomorphic input was not used in the design of the channel planform and morphology despite recommendations from a previous geomorphic survey on the Cole (River Restoration Project, 1994). Thus the design of the scheme appears to have neglected advice on the larger scale issue of sediment transport through the restoration reach. The restoration of the Brede was part of a wider watershed scale restoration programme (Nielsen, 1996b). This also included the creation of a floodplain lake, conversion of four concrete weirs to riffles and the construction of a series of sediment traps (Nielsen, 1996b). The consideration of sediment movement through the restored reach has thus been considered in a semi-quantitative method as part of a larger programme. Information on whether sediment transfer was considered in the design phase of both the Skerne was not available in the documented literature on schemes. However, Newson (*pers. comm.*) suggested that in the design phase of the Skerne sediment movement through the reach was addressed but was not considered to be a potential problem.

The techniques used on the Cole and Skerne have since been formulated into a manual of techniques by the River Restoration Centre (see website for more details) in the UK (River Restoration Centre, 1999). This provides background to the scheme as well as the use of particular techniques used in the two schemes. For example, descriptions on the design of meanders, backwaters, deflectors, riffles, bank revetments and details of techniques used to control water levels. The manual outlines the techniques used on the Cole and Skerne and therefore the details are only truly applicable to these sites. Care should be used when adapting these for other rivers.

Demonstration Erosion Control (DEC) project (adapted from Biedenharm *et al., in prep.)*

The Demonstration Control Project was initiated by the US Federal government in 1984 and aims to demonstrate a watershed systems approach to engineering rehabilitation and stream

management targeting 16 watersheds in the Yazoo basin, Mississippi. The watershed approach seeks to address problems associated with watershed instability such as erosion, sedimentation, flooding and environmental degradation. This is an interdisciplinary project with agencies such as the US Army Corps of Engineers and the US Department of Agriculture Natural Resources Conservation Service being responsible for the planning, design and construction of the project. The USDA Agricultural Research Service National Sedimentation Laboratory, the Corps of Engineers Waterways Experiment Station, University of Mississippi, US Geologic Survey and Colorado State University are responsible for research and monitoring.

Within the DEC watersheds the measured sediment yields prior to the DEC project were double the national average. This large yield resulted from the expansion of agriculture and the associated felling of virgin during the 19th Century. During the 20th Century, soil conservation efforts, coupled with channel straightening and construction of flood control dams further disturbed the fluvial systems leading to widespread incision through nick point migration. The DEC project represented the start of a comprehensive, intensive programme of watershed management incorporating watershed measures to deal with elevated runooff and sediment production, structures to prevent gullying and channel measures to re-establish an appropriate morphological stability. The objectives of the project were achieved through use of reservoirs, drop pipes, grade control structures and bank stabilization works. A key feature of the DEC project has been the extensive monitoring and research work that has followed the initial installation of the project. The monitoring program has established, for eaxmple, that DEC has been able to decrease sediment yields by 22% between 1992 and 1995 and so document the success of the project to date. DEC experience has demonstrated the potential for a multi-disciplinary approach to successfully manage sediment and related problems at the watershed scale. It has further established that compiling an historical account of the causes of instability, together with an accurate assessment of contemporary stability status of the channel system are essential steps in first understanding and then managing sediment dynamics and morphological instability.

2.2.2 Medium-Large scale Restoration projects

The Kissimmee River

The Kissimmee River, central Florida, USA, has been one of the largest restoration projects to date. Between 1962 and 1971 the 90km of the river was channelised to provide flood protection for central Florida (Toth *et al.*, 1993). The construction of the enlarged, straightened channel led to the loss of the river-floodplain connectivity, destruction of approximately 43,000 acres of river-floodplain wetland habitat and disappearance of 90% of the waterfowl throughout the river valley (Shen *et al.*, 1994). Prior to construction, flooding was an integral part of the Kissimmee system with large areas of the floodplain being inundated between 3 to 9 months of the year (Warne *et al.* 2000). The extent and duration of the flooding the Kissimmee was unique amongst rivers in North America (Toth, 1996). Almost immediately following channelisation recommmendations were made to restore the system back to its pre-channelisation status (Shen *et al.*, 1994).

A principle objective of the restoration was to improve the ecological integrity of the river through restoration of the flood pulse. A series of demonstration projects and studies were undertaken to evaluate the possibility of restoring the Kissimmee to its historical condition

(Toth *et al.*, 1993). Part of these studies was a basin-wide geomorphic study of the pre-canal system (Warne, 1998). A major goal of this study was to investigate how the timing, magnitude and distribution of water and sediment discharge could be used to optimise the restoration of the Kissimmee so that it interacted with its floodplain once again (Warne, 2000). This study found that there was little, or no, transfer of sediment from the Upper to the Lower Kissimmee basin. This, coupled with the absence of detrital overbank deposits on the floodplain, led Warne *et al.* (2000) to suggest that sediment transport was not a major process in the pre-channelised Kissimmee. Studies on the hydrological connectivity of the river-floodplain system suggest that to effectively restore the interaction of the river and its floodplain would require some upper basin modifications to the flow regime and backfilling of 46 km of the straightened channel (Toth *et al.*, 1993; Toth, 1996). This is currently under construction and is expected to re-establish flow through 90km of channel and provide interaction of the river and its floodplain over 11,000 hectares (Toth *et al.*, 1993).

The Kissimmee River has been extensively studied (see website for full list of publications) which has included a geomorphic survey (Warne, 1998; 2000). This concluded that sediment transport was not a significant process within the Kissimmee basin. Further studies have thus concentrated on the need to establish how best to renew the hydrologic connectivity of the Kissimmee with its floodplain. In this case the watershed study revealed the lack of regional sediment issues. Although negative, this finding was still informative in framing wider context for the restoration design

The River Danube

The Danube is one of the largest river systems in Europe and has possessed a long history of regulation and management.. Approximately 90% of the headwater tributaries have been dammed for hydropower during the last 50 years and much of the river has been extensively modified (Scheimer *et al.*, 1999). Rehabilitation of the river has concentrated on a 10km reach between Vienna, Austria, and the Slovakian border that, although partially regulated, represents one of the largest remnants of an alluvial landscape in Europe (Scheimer *et al.*, 1999).

The restoration of the Danube focused on measures that could be used to improve the hydrological connectivity of the river and its floodplain. Full scale restoration of the Danube was not deemed possible as a result of alterations to sediment transport regimes, nutrients and pollution level and additional constraints imposed by shipping and flood control (Scheimer *et al.*, 1999). A series of limnological investigations was undertaken on the 'Regulsbrunn' floodplain segment to document changes in abiotic, biotic and functional properties (Hein *et al.*, 1999). These were used to guide management strategies for the alluvial system and monitored post-implementation. For more details see Heiler *et al.*, 1995; Hein *et al.*, 1999; Scheimer *et al.*, 1999; Tockner *et al.*, 1999; Ward *et al.*, 1999.

Engineering measures to improve the hydrological connectivity and dynamics of the river-floodplain system included:

- lowering embankments, where natural inflow channels currently exist from the main thalweg into the floodplain system, by constructing a series of 30m wide overflow sills;

- adding extra openings at the inflow channels to ensure that a regulated inflow above the mean water level of –0.5m is maintained;

- lowering and widening weirs that currently control flows in the channels, within the floodplain system, to allow a shorter retention in the backwaters and to provide a more continuous flow of water.

(adapted from Scheimer *et al.*, 1999)

The focus of the pre-restoration studies was on the improvement of the ecological integrity of the floodplain system. Sediment investigations concentrated on the temporal variations in suspended sediment on a connected side arm (Heiler *et al.*, 1995; Hein *et al.*, 1999) in comparison to the main channel of the Danube. In the main channel of the Danube inorganic particle loads increased with rising water levels (Heiler *et al.*, 1995). In contrast, in the floodplain the degree of suspended sediment in the water was related to the level of connectivity of the side arms with the main channel (Heiler *et al.*, 1995). Consequently, the sediment continuity was considered in the design of the new restored 'Regulsbrunn' segment but as a result of the high degree of regulation that is still required due to the multifunctional requirements of the channel the scope for incorporating a dynamic system into the design was limited. Therefore, the scheme concentrated on restoration of the hydrological connectivity of the system, but with the hope that sediment connectivity would occur as a natural side effect of hydrological coupling between the main channel, its side arms and the floodplain.

2.2.3 Other projects

Watershed based projects

Several watershed based approaches have been used to guide the design of river management schemes in recent years. Watershed baseline studies and fluvial audits are increasingly being used to guide schemes designs in the UK (see 2.1.2; Environment Agency, 1998). Sear *et al.* (1995) outline how a fluvial audit was used to assess the volume of sediment transferred from the upper watershed of the Shelf Brook in the Pennines, UK and suggest appropriate management options. Sediment volumes were estimated using four techniques, the results of which were used to aid the design of gravel sediment traps as well as the maintenance schedule of these structures (Sear *et al.*, 1995). The four techniques used were:

- "modified Schoklitsch bedload equation for mountain streams;
- Bagnold stream power equations;
- Modified Newson watershed area equation;
- Transport length linkage of sediment supply and storage zones."

(from Sear *et al.*, 1995, p645)

The use of a watershed baseline survey (Environment Agency, 1998b) to determine reach conservation values is outlined in Downs and Thorne (1998). Conservation valuations were used to prioritise reaches for rehabilitation for the River Idle, North Nottinghamshire, UK. A variety of watershed, corridor and instream measures was proposed. The design of the instream measures needed to satisfy geomorphological, flood defence and conservation interests and thus the rehabilitation design was required to:

1. accommodate the prevailing trend for sedimentation to achieve to geomorphic sustainability without a long-term commitment to frequent and costly operational maintenance;

2. meet statutory standards of flood defence through ensuring that the rehabilitation structures do not raise flood flow stages unacceptably;

3. deliver a permanent improvement to fishery and conservation value of the river through the manipulation of the flow field, via the rehabilitation designs, to prompt morphological recovery and create habitat diversity through the natural processes of scour and fill.

(adapted from Downs and Thorne, 2000)

In addition selected hydraulic models were used to test the instream designs to ensure that they did not compromise flood defence levels (HMODEL2, HECRAS and FCFA) and to help determine the most appropriate siting for the deflectors (BENDFLOW). For more detail on the modeling results see Downs and Thorne (2000).

Immediately prior to installation, and a further 6 times since, morphological monitoring and project appraisal have been undertaken to provide sediment budgets at a variety of different types of deflector designs (see Skinner, 1999; Environment Agency, 2001; Skinner *et al.*, *in prep.*). The monitoring of the deflectors has now been undertaken over a 5-year period. The deflectors have largely achieved their objectives increasing morphological diversity through bed scour and fill. For example, at deflector 6D, between the January 1996 survey and the June 2001 survey there has been a net loss of sediment, through scour, around the deflector assemblage of 45.7m^3. However this figure disguises the fact that the change around the assemblage was a loss of 72.39m^3 of sediment whilst 26.72m^3 was deposited. Scour was largely concentrated around the tip of the deflector whilst deposition was particularly evident immediately downstream (behind the structure) of the deflector. The individual effectiveness of the deflectors is dependent on the type, size, shape and projection into the low flow channel. Through the use of the BENDFLOW model a series of deflectors were installed throughout the reach to prompt the development of a new low flow channel. This has again been largely accomplished. The long-term success of the scheme is subject to watershed proposals, which have been adopted in the watershed management plans, being implemented. If this is not performed the scheme is prone to the movement of sediment slugs through the system that could jeopardise permanent success. The Idle rehabilitation scheme has thus been a successful attempt at using the long term trend for sedimentation to evolve a design that could prompt the recovery of a new, sustainable, low flow channel.

Schemes that have recognised watershed scale processes in their design

A review by Brookes (1996) of restoration experiences in Northern Europe and Nielsen (1996b) in Denmark suggest that increasingly watershed scale processes are being incorporated into the design of schemes. In the UK Brookes (1996) documented several case studies that had taken into account the likely affects of watershed scale processes. On the Redhill Brook, Surrey, the deposition of fine sediment moving from upstream was anticipated as a result of mining works further upstream. However, Brookes (1996) suggested that this was still difficult to mitigate against in the project design. On the Wraysbury River, Berkshire, Brookes (1996) outlines how the strategic placing of deflectors as part of a wider flood control project has successfully developed a low flow channel. This was achieved as the deflectors led

to the preferential deposition of sediment in their immediate vicinity, whilst the narrowed channel kept the gravel bed free of silt. Unfortunately only a qualitative assessment of the scheme was made, with repeat photographs, and thus there were no calculations undertaken on the actual volume of sediment stored behind the deflectors. The instatement of riffles has been a common feature in UK restoration projects. The installation needs to be made from sediment with a calibre that will remain stable in moderate to high flows. Brookes (1996) outlines how this was achieved on the River Blackwater, Surrey, through the placing of several tonnes of coarse angular floodplain gravel designed to enhance morphological diversity through raising the bed topography at particular sites.

In Denmark legislation has existed since 1982 that has provided the platform for restoration (Nielsen, 1996b). However until 1995 restoration was largely undertaken on a piecemeal basis without considering the potential for watershed scale improvement (Nielsen, 1996b). The most common form of restoration technique was the integrated use of a number of single structure measures (Iversen *et al.*, 1993). However, recent projects on the River Brede (see section 2.2.1) and the River Torning in southern Jutland have both incorporated watershed based principles (Nielsen, 1996b). These have considered the sediment continuum in the design even though there has been no detailed outline on how this has been achieved.

There have been a number of other European projects that have considered sediment transfer through the restored reach. Habersack and Nachtnebel (1995) and Muhar (1995) outline such an approach on the River Drau, Austria. Predictions of sediment movement were made in the design phase of the project using a bedload sampler (Helley-Smith) and a numerical sediment transport model (Habersack, *pers. comm.*). In addition, subsurface and surface material samples were collected (Habersack, *pers. comm.*). Key features in the scheme included the excavation of a new side channel leading to the creation of an island and the installation of groynes to maintain flow depth through scour. After the scheme had been constructed topographic monitoring was performed using an echo sounder mounted to a boat. In addition grain size distributions were calculated using an underwater video camera linked to a picture analysing program. These techniques were used to determine the temporal changes in river morphology. After one year net aggradation had occurred thus reversing the trend for degradation and achieving one of the primary aims of the scheme. The results of this project are being used to guide future restoration projects in an extended area of 60km around the scheme (Habersack and Nachtnebel, 1995). This will provide the opportunity to examine the more regional impacts of the scheme itself.

Jungwirth *et al.* (1995) and Muhar (1995) outline restoration measures that have been performed on the River Melk, Austria. These were installed to improve the habitat of the previously straightened channel. A major part of the scheme was also to remove the paved bed to form a more natural bed substrate (Jungwirth *et al.*, 1995). The 1.5km restored section of the Melk was surveyed once before the scheme was installed and 3 times after at annual intervals (Jungwirth *et al.*, 1995). Each survey consisted of 300 cross-sections (Jungwirth *et al.*, 1995) and at each cross section water depths, flow velocities and substrate types were measured every 2m. The monitoring of the scheme revealed how the improved habitat heterogeneity was matched by a significant increase in the density and biomass of the fish community. Although the scheme has been monitored extensively it was not clear how sediment movement had been considered into the design of the scheme.

An important consideration in both restoration schemes and other engineering projects is to ensure that the local environmental setting is considered in the design of the project. An illustration of this is described in Shields *et al.* (1998) who outline an approach to rehabilitating warmwater streams damaged by channel incision in Mississippi. Their designs were "guided by both conceptual models of incised channel evolution and fish community structure in small warmwater streams" (Shields *et al.,* 1998, p63). Shields *et al.* (1998) concluded that efforts for rehabilitation should be focused in aggradational reaches in downstream sections of incised watersheds.

Projects that have adopted a reach focus

A number of schemes have been installed with little consideration of the long-term sediment dynamics of the reach. This is either as a consequence of the scheme being of small scale such as the placement of boulders to improve fish habitat (Brittain *et al.*, 1993), or through taking a reach scale focus ignoring the wider scale watershed scale processes (Nolan and Guthrie, 1998). The neglect of watershed scale processes could potentially threaten the long-term success of the scheme. Nolan and Guthrie (1998) compare two schemes in the Mersey Basin, NW England, one which has included geomorphic assessment in the design (Whittle Brook) and the other which had no geomorphic input at any stage (River Alt). On the Whittle Brook a geomorphic assessment was performed as a key component of the feasibility and final design plans (Nolan and Guthrie, 1998). This enabled the scheme to be designed with respect to the catchment sediment system and initial interim reports suggest that the Whittle Brook is adjusting naturally to the new modifications. In comparison, the Alt still had an engineered appearance with smooth engineered curves in a sinuous channel (Nolan and Guthrie, 1998). The consideration of watershed sediment system, through the use of a geomorphologist, in the Whittle Brook led to a system that possessed more natural channel characteristics than that of the Alt that had no such input (Nolan and Guthrie, 1998).

2.2.4 Other issues in regional sediment management

This literature review has focused on whether sediment has been considered in the design of engineering schemes, such as restoration projects. However, it is also useful to allude to other issues that have been identified in the literature. In particular this relates to dam removal (Shuman, 1995); the effects of hydropower schemes on sediment continuity (Erskine *et al.*, 1999): the use of settling ponds to deal with sedimentation (Verstraeten and Poesen, 1999); the neglect of sediment transfer issues in the construction of a flood defence channel on the Yellow River, China (Shu and Finlayson, 1993).

Shuman (1995) reviews the likely environmental impacts of dam removal in the USA. The average age of dams in the USA is 40 years. Shuman (1995) argues that many dams are in need of safety rehabilitation, the cost of which is uneconomic. Decommissioning might be the most appropriate alternative. Dam removal will have significant effects on the sediment system and its connectivity. Specifically, concerns relate to the remobilisation following dam removal of sediment stored in the reservoir, accelerated aggradation and floodplain dynamics downstream; changes to river channel morphology both up and downstream and drawdown effects (Shuman, 1995). It must be concluded that it is important to consider larger scale regional sediment dynamics when planning the removal of dams.

Erskine *et al.* (1999) reviews the hydrogeomorphic effects of the installation of a large hydroelectric power station on the Snowy River, Australia. Since 1967 there have been large scale hydrological and geomorphic effects downstream of the river. The construction of large dams, such as the Jindabyne dam, has led to a large reduction in downstream suspended sediment yield. This is now all accumulating behind the dam. This, along with the flow regulation, has had immediate downstream effects, such as spatial shrinkage. In the Jindabyne gorge downstream of the dam this is occurring in the order of 5-95% through a variety of processes, including:

"Tributary mouth bar formation;
Side bar and bench formation;
Pool filling with biogenic sediment;
Native and exotic vegetation invasion and consequent stabilisation of recent deposits."

(Erskine *et al.*, 1999, p13)

This has led to a decrease in channel habitat. Erskine *et al.* (1999) outline the need for the development of a new environmental flow regime for the Snowy River. This case study shows, again, the paramount importance of taking into account watershed scale processes when designing any type of scheme.

Verstraeten and Poesen (1999) detail the problem of 'muddy floods' in Belgium. They suggest that storm runoff often exceeds capacity of drainage ditches or sewers thus leading to large flooding and deposition of fine sediment. A common way for authorities to deal with the flooding problem is in the construction of retention ponds. Unfortunately sedimentation is rarely accounted for in the design of these ponds necessitating frequent dredging and thus raising the costs of maintenance. The sedimentation of these ponds has enabled Verstraeten and Poesen (1999) to form an estimation of the sediment yield in these watersheds and thus help define the scale of the problem. They conclude that sedimentation rates are highly variable and have been heavily influenced by land-use changes and the topography of the landscape.

Shu and Finlayson (1993) detail the unsustainable design of flood defences on the Yellow River, China. Since 1947 the river authorities have contained floods within artificial levees preventing the river from changing its course. Rapid bed sedimentation between the flood embankments has raised the bed level of the Yellow River as much as 10m above the surrounding floodplain. Shu and Finlayson (1993) suggest that as the design flood for the system is only 60 years there is a real possibility of a major disaster occurring. They suggest that the current management strategy is not sustainable in the long-term and the most appropriate option would be to breach the levees at strategic points coupled with the development of an advanced warning system that can be used to warn the people affected by the scheme. This case study illustrates how disruption of the regional sediment transfer system can lead to extensive problems over decades of operation and re-emphasizes the vital importance of adopting sustainable solutions to flood control and river management problems.

2.2.5 *Summary*

A review of various projects suggests that the extent to which regional sediment transport and transfer have been considered in the design of schemes has been variable. Recently there have been a series of qualitative and semi-quantitative approaches that have been used to try and account for the likely sediment movement through a project reach. The fluvial audit and watershed baseline approaches (Environment Agency, 1998b) are becoming increasingly popular within the UK in watershed management. The integrity of the Fluvial Hydrosystem has recently been recognised as a necessary preliminary condition for development in a recent law (1992) in France (Piegay, 1994). This has been used to develop watershed management policies such as those on the Rhone watershed (Piegay, 1996). As yet there has been little documented evidence that the River Styles approach (Brierley and Fryirs, 2000) has been used to guide the river management programmes although it has been incorporated into the Australian national guidelines for river rehabilitation (Rutherfurd *et al.*, 2000). At the project reach scale a variety of approaches has been used. A novel technique has been developed by Soar (2000) that evaluates the upstream supply and downstream demand of sediment in the design of a scheme to account for sediment continuity. Other techniques have used empirical measurements of bed load or numerical models (see Habersack and Nachtnebel, 1995) to establish the sediment transfer through the reach.

The literature review alludes to various documented approaches and thus can be seen as a review of the 'best practice' techniques. It is important to consider that in practice many small projects are not well documented and are not likely to use these techniques. It is of paramount importance local, smaller scale projects take into account river processes at a watershed scale in their design (Boon, 1998). Of key importance is the consideration of sediment supply from upstream as instream sedimentation can lead to loss of conveyance oin flood control channels and obliteration of restored features (Brookes, 1996). This has been well documented in the USA (e.g. Frissell and Nawa, 1992; Miles, 1998). In the design of flood control and restoration schemes, Muhar (1995, p472) suggests that the following criteria should be considered:

"Bed load transport (input/output);
Discharge regime;
Daily and seasonal temperature regime;
River continuity: both the lateral, longitudinal and vertical interconnections within the system;
Wetland dynamics (flooding);
Morphological and hydraulic characteristics of the channel (horizontal, longitudinal and cross sectional profiles) in connection with natural velocity and substrate distributions, as well as the structure of the river bed and bank zone."

If reliable methods were developed to assess these parameters it should help increase the likely chances of success in designing future schemes that maintain the sediment continuity of the system.

The review of the literature suggests that some schemes are being monitored post-installation. These include the restoration projects on the Cole, Skerne and Brede (Sear *et al.*, 1998; Kronvang *et al.*, 1998), the Kissimmee (Toth, 1996), the Danube (Scheimer *et al.*, 1999; Heiler *et al.*, 1995; Hein *et al.*, 1999), the River Idle (Skinner, 1999; Skinner *et al.*, *in prep.*) and various Austrian rivers such as the Drau and Melk (Habersack and Nachtnebel, 1995;

Jungwirth *et al.*, 1995; Muhar, 1995). The types of schemes that are being monitored tend either to be demonstration projects supported by various institutions, large scale projects or smaller scale projects that have had a heavy academic involvement through universities. More generally Brookes (1996) suggests that there is routinely little, or no, monitoring of either sediment loads or morphological channel changes following engineering construction. To obtain a more detailed perspective of contemporary post-iconstruction monitoring and appraisal in fllod control and rehabilitation projects a review of current literature is presented in the next section.

2.3 Current documented post-implementation practice

It is important that both monitoring and post-project appraisals be undertaken as a strategic part of a management cycle (Watts and Fargher, 1999). However, the development of post-installation practice is largely in its infancy. Although there are a number of schemes that have included examination of project performance (see section 2.2 for more details) in the vast majority of cases, monitoring has been absent or deficient (Brookes, 1996). Monitoring is essential in determining the success of future appraisals and it is recommended that at least 10 years should be performed to establish whether a scheme has been successful (Brookes, 1996; Kondolf and Micheli, 1995). The documentation and dissemination of these results provides the opportunity to inform future projects about context-specific 'good' and 'bad' practice (Downs and Kondolf, *submitted*). It also assists the development of the rehabilitation process through ensuring that designers can build on present successes, and reduce failures (Lucas *et al.*, 1999) by applying this information in the planning and implementation of future schemes (Watts and Fargher, 1999).

For appraisals to succeed it is important to state project goals along with testable criteria, from which to base an appraisal, in the design phase of the scheme (Brookes, 1996; Brookes *et al.*, 1996; Watts and Fargher, 1999). This is not common practice (Kondolf and Micheli, 1995; Watts and Fargher, 1999) and, as a result, contemporary evaluations are largely reactive - relying on basic objectives, design plans and retrospective baseline criteria from which to judge the success for schemes. For the development of the process it is essential for systematic approaches for design, monitoring and evaluation of projects are developed (Brookes, 1996). Improvements in our ability to set appropriate objectives for projects, understand the problems involved and adopt the right strategies, have the potential to profoundly influence the progress of stream rehabilitation (Ladson *et al.*, 1999). To this end research at the University of Nottingham has recently focused on the development of a geomorphic Post-Project Appraisal procedure (Skinner, 1999; Environment Agency, 1998b). This has identified the need to assess the morphological success of the scheme through the completion of a compliance audit and performance audit. The results of these are brought together in a geomorphic evaluation. This procedure has been furthered in this project to focus on the assessment of the sediment dynamics of the project reach within the context of watershed scale sediment continuum. This technique is outlined in section 4.0 following a review of responses from practitioners regarding the consideration of sediment dynamics in the design, monitoring and appraisal of restoration/engineered river management schemes.

3. REGIONAL SEDIMENT MANAGEMENT - CONTEMPORARY PRACTICE IN REGIONAL ASSESSMENTS AND RESTORATION DESIGN

3.1 Introduction

An investigation was performed to explore contemporary practice in regional sediment management through contacting selected practitioners throughout the world. In total 36 people were contacted in 12 different countries. 12 individuals replied, enclosing relevant commentaries, information and literature (see Appendix 1 for list of respondents). A follow-up questionnaire was sent to the respondents to seek further input from them, but only 3 completed questionnaires were returned (see Appendix 2 for copy of questionnaire). The questionnaire dealt in more detail with regional sediment management practice considering the design, monitoring and appraisal of projects. The results outlined below were synthesized from both the questionnaire responses as well as individual e-mails received.

3.2 Approaches and methods used in regional sediment management

A general consensus amongst the correspondents was that the sediment dynamics of a system are rarely considered in the design of schemes. This was highlighted in the questionnaire feedback where the responses indicated that less than 20% of schemes consider regional sediment dynamics in their design (see Figure 4). One respondent suggested that the objectives "are typically based on site specific needs, without much consideration of watershed-scale processes that deliver water and sediment." A major problem identified by another respondent was the lack of appropriate methodology in that:

> "reliable methods for determining sediment loads are not widely documented."

Some projects have taken a watershed view of sediment dynamics. One respondent referred to the design regulating reservoirs and river training systems for the Missouri and Arkansas Rivers designed between 1930-1960. In planning the projects it was recognised that there would be a high sediment trapping efficiency in the reservoirs. It was recognised that this would, in turn, drive channel adjustments downstream of the dams, and generate channels with morphologies to pre-project conditions. In fact, changes have occurred along both rivers broadly as anticipated, leading to problems of channel stability and bank erosion that have required further engineering works. While flood control, hydropower and river regulation functions of the schemes have been successful, channel adjustments have had deleterious environmental effects including negative impacts on endangered species, requiring on-going mitigation and further engineering solutions.

Of the schemes that have considered likely sediment transfer in their design the scale at which this has been considered has been variable. Questionnaire results (Figure 5) suggest that some schemes have taken a watershed perspective whilst others have been limited to the reach scale. Largely, this seems to be dependent on whether the agency responsible for the scheme has a national, regional or local remit and authority. For example, one return indicated that in 80%

of schemes the scope of sediment transport considerations was limited mainly by the authority and area of authority of the constructing agency and rather than the vision of the technical and engineering design team. In contrast, another respondent stated that 100% of schemes that he had personally been involved with had taken a watershed perspective. This can directly be attributed to the fact that this respondent is a senior consultant with sufficient influence over the feasibility and design studies to ensure that surveys are extensive as well as intensive. This respondent also pointed out however that most of watershed scale assessments are qualitative and that ideally the methods currently available to support regional assessments of sediment dynamics should be enhanced to produce quantitative or at least semi-quantitative information.

UK respondents acknowledged that strategic watershed baseline surveys and fluvial audits are increasingly being undertaken before a scheme is installed. Incorporation of these steps into the design process has resulted from policy changes in the UK Environment Agency although uptake is variable between different regions. Assessments of regional sediment dynamics remain mostly qualitative and project-centered, although one respondent suggested that:

> "a few more strategic approaches have been conducted in support of watershed management of sedimentation and erosion."

A variety of techniques are used to provide an estimate of sediment movement in the design of river engineering and management schemes. Approaches adopted range from application of geomorphic rules and relationships, through the collection of field samples and use of sediment transport equations to full numerical modelling. Empirical approaches mentioned by respondents include qualitative inspection of sediment features and morphology in nearby reference reaches, visual assessment of sediment loads, field measurements of sediment transport and derivation of site specific watershed area/sediment yield relationships. The determination of which technique to use appeared largely to depend on the resources available for the investigation.

One respondent detailed a threshold analysis method that was used to estimate the boundary shear stress required to move the largest particle present at each point along the system. This estimate may be used to design riprap or riffle features that will remain stable even under the maximum fluvial attack. This method is applicable only to gravel-bed rivers with highly non-uniform sediments. It is not a suitable technique for sanded systems and relatively uniformly graded gravels. A more advanced approach is to use a 1-dimensional hydraulic model with a sediment transport module to estimation the mobility of bed material under pre- and post-project conditions. Sediment transport equations that have been found by respondents to be useful for application in this manner include those of Bagnold and Schoklitsch which are appropriate to:

> "determine flux divergence impacts in low energy/high energy situations, respectively."

In this type of application, it should be noted that it is not the absolute accuracy of the equations that is important, but their ability to consistently detect the differences between reach-scale sediment inputs and outputs that drive regional morphological adjustments and long-term instability in the sediment transfer system.

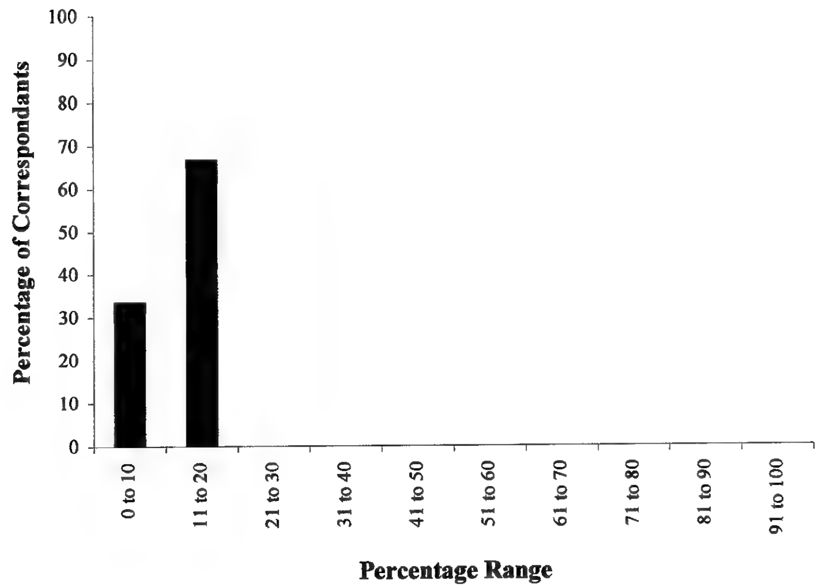


Figure 4: Graph to show the percentage of schemes that have considered sediment movement in the planning of the scheme

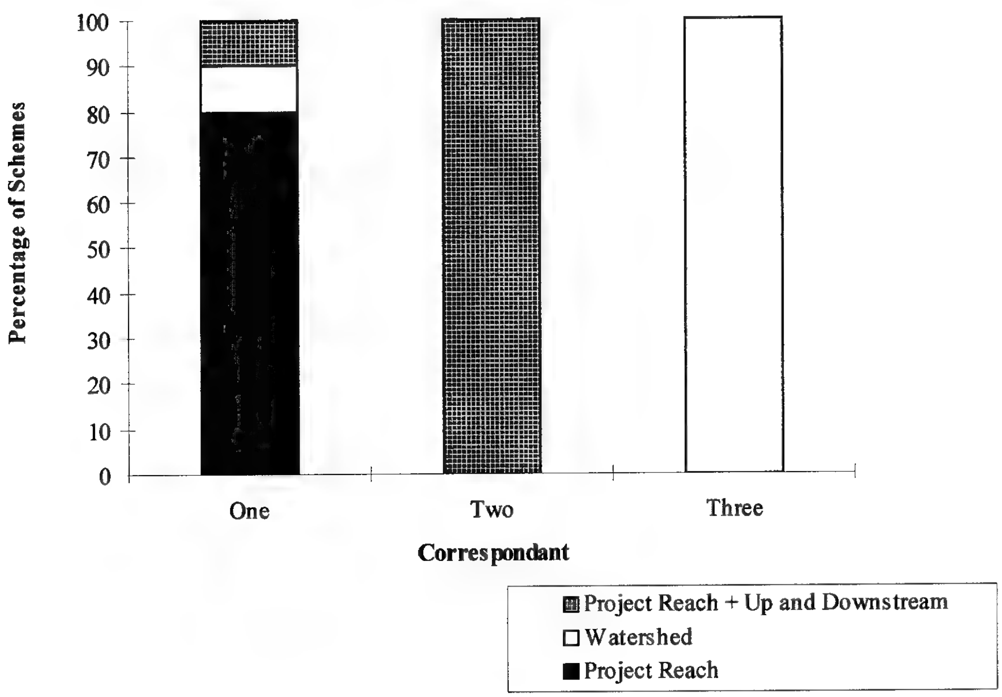


Figure 5 : Graph to demonstrate the scales at which sediment movement has been examined

3.3 Contemporary practice in monitoring and post-project appraisals

Monitoring and appraisal of schemes are rarely performed. Survey results indicated that monitoring (Figure 6) was undertaken in less than 20% of schemes while a post-project appraisal (Figure 7) was undertaken in fewer than 10% of schemes that respondents had been involved in. Of those schemes that have incorporated monitoring a common procedure used was the measurement of cross-sections. The temporal and spatial spacing of measured cross-sections varied between schemes. In other schemes regularly spaced sections were replaced by measured cross-sections were sited at specific sites of interest, such as riffles or in-channel flow deflectors. A common objective was to provide the data required to perform a sediment balance calculation for pre and post-project sediment accumulation/loss in the reach. Where sediment mass balance is to be attempted, one respondent outlined how echo soundings at regularly spaced cross-sections may be supplemented by measurements at random intermediate points to massively increase the accuracy of a digital elevation model (DEM) used to represent bed topography and topographic changes in the study reach. Temporally, cross-sections are uauually measured annually, semi-annually, or following major events.

Bed sampling and particle size analysis were frequently used to determine changes in sediment composition through space and time. Often sampling concentrates on monitoring changes in the surface armour at riffles. Sampling methods employed either a bulk sampling or pebble counts. In some schemes on gravel-bed rivers other methods were required to capture the fine fraction of bed sediment (for example, freeze coring) which tends to be lost when conventional samples are collected..

Channel stability and morphological changes are commonly assessed using cross-sectional measurements, but the data so collected may miss important but temporary changes that occur during floods. For general scour of the bed, scour chains have been employed, although with mixed success. Cross-sectional surveys seldom supply reliable indications of bank erosion and bank profile adjustments. Bank erosion pins have historically been used to assess bank erosion, although more recently, ground-based stereo photographs analysed by photogrammetric techniques have become more popular.

Other monitoring measures outlined by the correspondents have included a fluvial audit at each evaluation date to record changes each year through standard forms. This regular documentation provides important qualitative and anecdotal evidence of channel changes that can flesh out the data provided by re-surveys at monumented cross-sections.

In the questionnaire, respondents were asked to report the success rate of schemes that had been appraised. The results (Figure 8) suggest that very few schemes were considered to be either a complete success (~3%) or a total failure (~3%). Examples of total failures referred to by respondents included the destruction of grade control structures in one scheme and collapse of bio-engineered structures in another. Just over a fifth of schemes (about 22%) were judged to have achieved a high degree of success. These schemes were considered to be largely successful in that they met their engineering and environmental goals while achieving sediment continuity through the project reach and so avoiding a heavy commitment to rehabilitation and maintenance. The reason they fell short of total success was often linked to the negative impacts of engineered and unnatural channel forms and structures on environmental and aesthetic values. Most schemes were judged to be either partially successful (about 38%) or

largely successful and working as anticipated, but with failure of certain elements that were repairable (average 33%). In the case of schemes assessed as partially successful, the most common problem was that the scheme was unsustainable in the long-term without significant on-going works to rehabilitate the channel – works that went beyond routine maintenance. These results indicate that the overall success rate of schemes is still generally low and that there is room for improvement in the design of flood control and restored channels that achieve multi-functional goals while being sustainable within their regional sediment context.

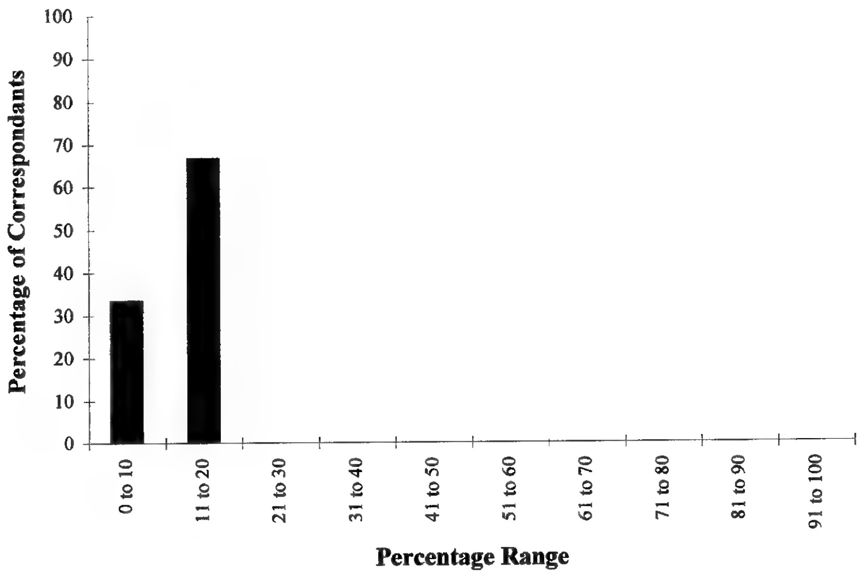


Figure 6: Graph to show the percentage of schemes that have had monitoring undertaken post-installation

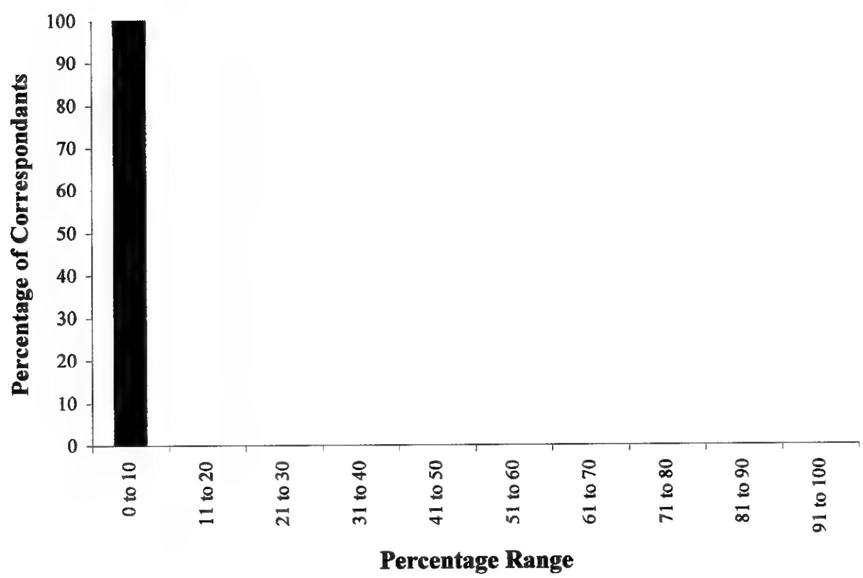


Figure 7: Graph to show the percentage of schemes that have had appraisal undertaken post-installation

Figure 8: Success rate of schemes judged via a Post-Project Appraisal

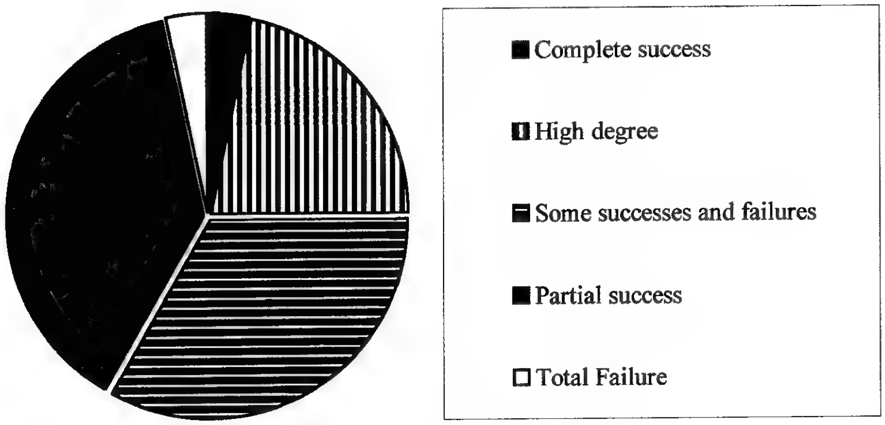


Figure 8: Success rate of schemes judged via a Post-Project Appraisal

3.4 Summary

The results gathered from a variety of respondents around the world suggest that the regional sediment dynamics of the system have historically been rarely considered in the design of schemes. However, specialist river engineers and geomorphologists do recognise the paramount importance of understanding the regional sediment context for a flood control or restoration scheme. For example, one respondent stated with regard to river restoration:

> "maintenance of the mass balance of sediment is *the* critical issue, and projects that ignore this are destined for failure."

There is evidence to suggest that the insight possessed by specialists is slowly filtering through to project managers and general practice in that watershed wide processes are now being considered in the design of schemes. Monitoring and appraisals of schemes are rarely undertake but in the few schemes that have included PPA, post-project monitoring and appraisals have been found to be valuable project components that allow lessons to be learned, success to be demonstrated and best practice to be disseminated. Experience shows that the PPA process is currently hampered by the fact that no standardised post-project appraisal procedure exists, particularly with respect to regional sediment management. In this regard a geomorphic Post-Project Appraisal procedure developed at the University of Nottingham was identified as being potentially of use as the basis for a PPA tailored specifically to regional sediment management. A review of this procedure is undertaken in section 4 to investigate its applicability for use in assessing regional sediment management of engineered channels within morphologically active fluvial systems.

4. GEOMORPHIC APPROACHES RE-EVALUATED

4.1 Introduction

A Post-Project Appraisal (PPA) procedure was developed as part of a research project undertaken at the University of Nottingham co-funded by the Environment Agency of England and Wales. The research aimed to provide a standardised approach to assess the performance of environmentally-aligned flood control and channel rehabilitation schemes. The resulting UoN approach is shown in Figure 9. The procedure was developed in a format that allows its skeletal structure to be adapted to suit the needs of end-users such as project designers assessors. A brief review of this procedure presented here to form the basis for explanation of the adaptations and modifications performed to tailor the method to regional sediment issues.

The geomorphic Post-Project Appraisal procedure was developed through incorporating some of the main theories of Environmental Assessment process into a geomorphic framework. In the environmental assessment literature Sadler (1988) outlined three major objectives that any PPA should aim to meet. These are:

1. "in project regulation it should ensure that the activities are conforming to previously established conditions;
2. it should provide an opportunity to manage any unanticipated effects;
3. it should aid field development through an improvement of practices."

(Sadler, 1988, p131-132)

PPA should also allow an early dissemination of results so that future schemes in similar settings will avoid repeating past mistakes (Sadler, 1988) and so that valuable experience gained in one project can inform future projects (Beschta *et al.*, 1994). Sadler's basic ideas for the requirements of a PPA were adapted to form a structure that could be used to assess river rehabilitation schemes. The principal objectives of the geomorphic PPA approach are to:

- determine whether the scheme was constructed as planned;
- ascertain whether any unanticipated effects were occurring through comparing the performance of the scheme with stated objectives outlined in the design phase;
- provide the opportunity to identify any requirements for necessary maintenance work;
- aid the identification of particularly successful techniques used in various schemes to develop a 'best practice' approach;
- provide an indication of whether the scheme has met short-term objectives and indicate whether the scheme can be sustainable over a longer duration.

The PPA procedure should enable an evaluation of the degree to which morphological stability, or adjustment, has occurred following construction. This is rare performed in current evaluation programmes (Kondolf and Micheli, 1995; Brookes, 1996b). It is envisaged that, through indicating whether the scheme has achieved short-term objectives and whether it can be sustainable in the longer-term, the PPA will enable the overall success of the scheme to be judged. The outcomes of various techniques and measures, whether successful or not, should be published for the benefit of river managers (Brookes *et al.*, 1996). The stages of the PPA developed at University of Nottingham are shown in Figure 9.

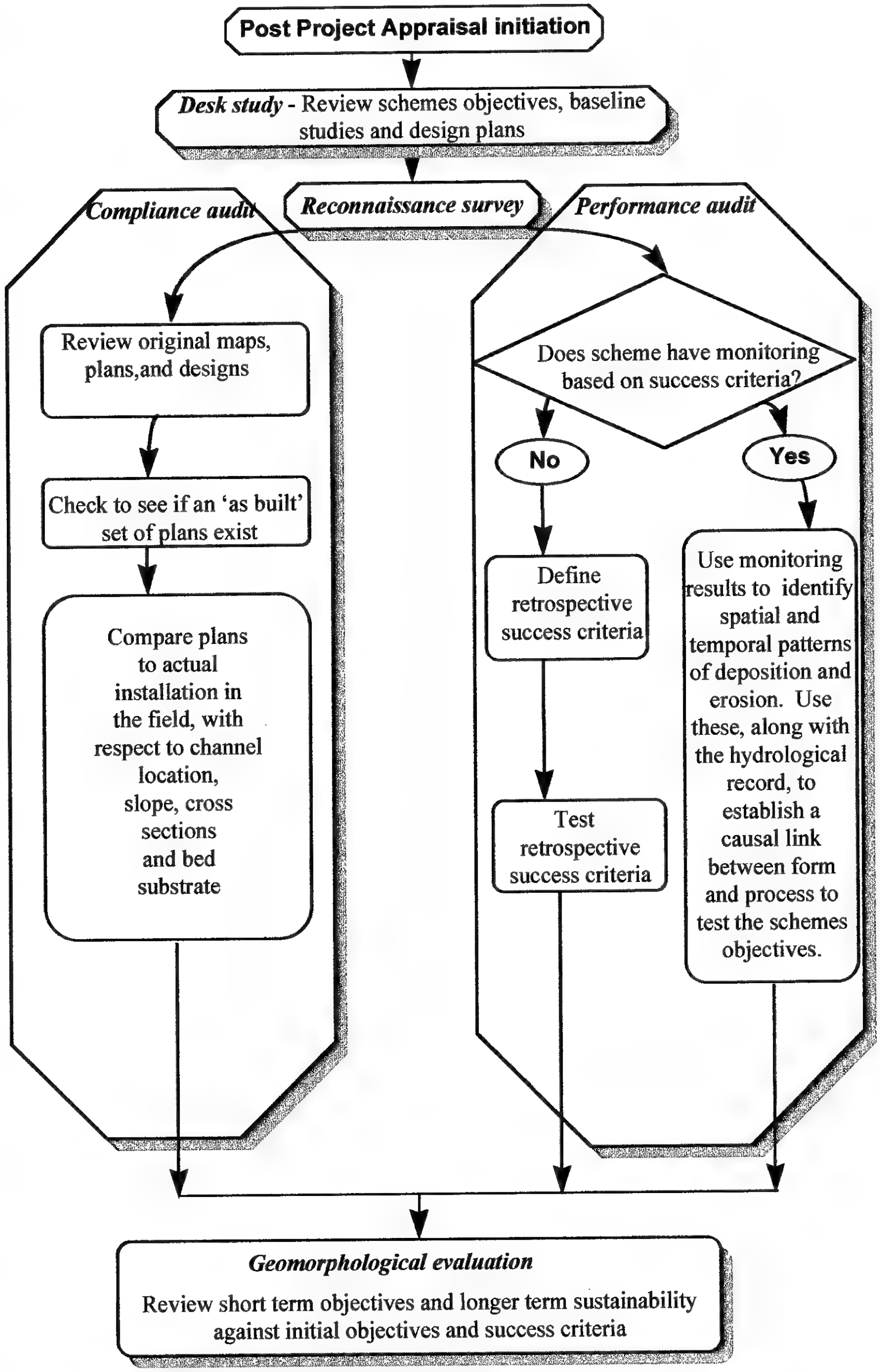


Figure 9: Geomorphic Post-Project Appraisal Procedure (adapted from Skinner, 1999)

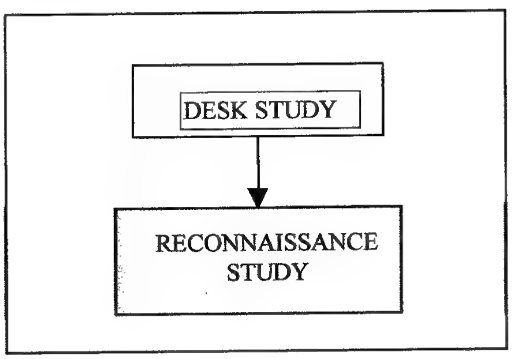
4.2 Geomorphic Post-Project Appraisal procedure

4.2.1 Desk Study

DESK STUDY

The desk study is undertaken to collect information relating to the pre-project state of the environment and background material on the scheme itself. The types of information to be obtained include any documents related to the scheme, such as an options evaluation report, a geomorphic assessment, any biological reports and design plans and maps. Along with this specific information on the scheme, other useful reports include documents relating to the area or reports on previous work that have been undertaken in the watershed. This information can be used, along with monitoring data and stated success criteria, to determine areas that require further investigation and/or measurement within the PPA.

4.2.2 Reconnaissance Study



Commonly, insufficient site-specific geomorphological information exists to support a Post-Project Appraisal. Consequently, a river reconnaissance survey is likely to be required. This survey provides data, which can comprise of either quantitative measurements and/or qualitative interpretations depending upon the needs of the surveyor (Downs and Thorne, 1996). Whilst undertaking the survey it is also important to continue it up and downstream where interactions are thought be significant (Downs and Thorne, 1996). River reconnaissance surveys achieve this appraisal by collecting and collating inventories of morphological features using a *pro forma* checklist (Thorne *et al.,* 1996). Thorne (1998) summarised the purpose of river reconnaissance surveys to:

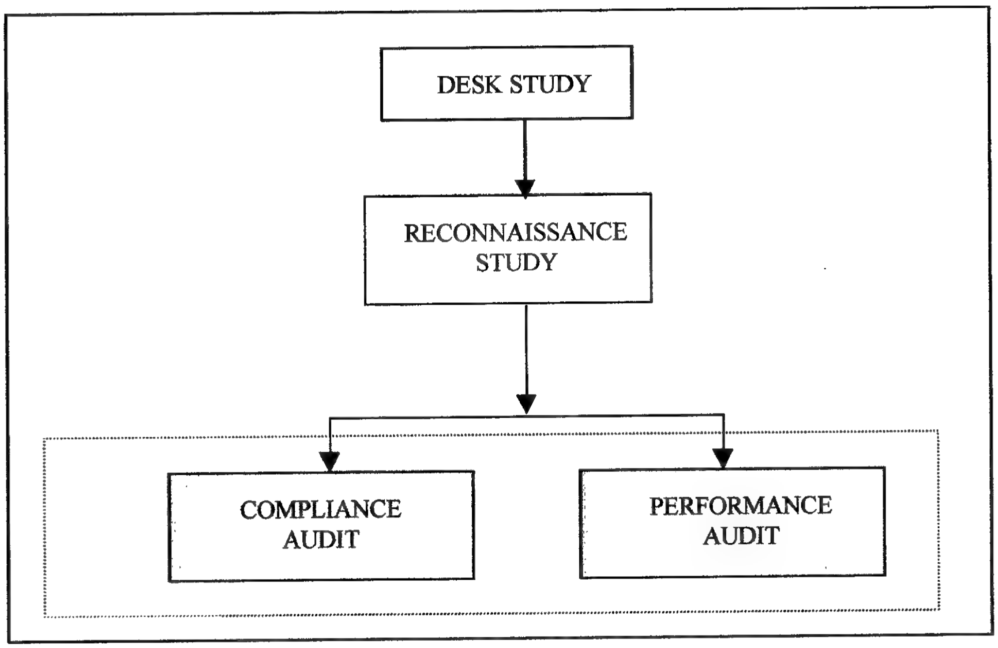
- "supply a methodological basis for field studies of channel form and process;
- present a format for the collection of qualitative information and quantitative data on the fluvial system;
- provide a vehicle for progressive morphological studies that start with a broadly focused watershed baseline study, continue through a fluvial audit of the channel system, and culminate with a detailed investigation of geomorphological forms and processes in critical reaches;

- supply the data and input information to support techniques of geomorphological classification, analysis and prediction necessary to support sustainable river engineering, conservation and management."

(Thorne, 1998, p37)

Thus river reconnaissance surveys can be used in a PPA to assess the scheme within its environmental context and help distinguish the required baseline criteria.

4.2.3 Compliance Audit and Performance Audit



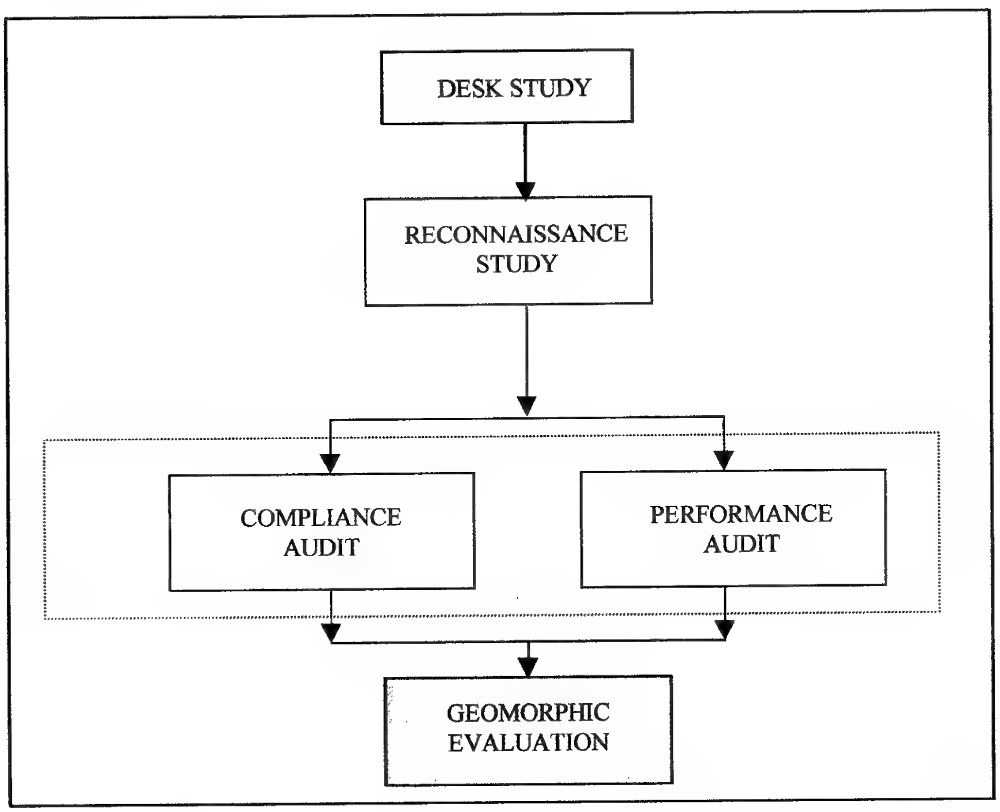
Following the initial collection of background information through the desk study and reconnaissance survey the assessment part of the PPA procedure now begins. The first stage comprises of a compliance audit and a performance audit which are run concurrently during the assessment procedure.

The compliance audit is used to review whether the scheme was constructed according to approved design plans. This is an important starting point since the location and form of structures often deviates significantly from the original design plans during construction due to miscommunication, contractor error or unforeseen circumstances. It is therefore essential first examine whether a scheme has been installed as outlined in the design plans. Differences between these plans and actual installation may be responsible for unexpected performance attributes or failure of the scheme, irrespective of the validity of the original design. Key parameters that should be checked against design values in a compliance audit include; channel slope, cross-section and bed material; and the dimensions and materials used in construction of structures and habitat features. These variables should be audited as a minimum, but it is advised that each scheme should be judged on a case by case basis, since other variables might be just as important in different situations.

The performance audit establishes the morphological impacts of the project and compares them to those predicted when the scheme was designed. This is based upon the assumption that the scheme has been constructed as initially planned. If this is not the case then 'professional judgement' will be required to assess how the actual design of the constructed project might have affected geomorphic processes. From this, an attempt is made to estimate how the variations would have affected the final outcome. The first stage of the procedure is to determine whether any pre-project and post-project monitoring data exist that could be used to assess both the temporal and spatial success of the scheme. Monitoring data can be used to identify whether any significant changes have occurred since the installation of the scheme. This might be either due to a design failure or system recovery following the installation of the scheme. This could include significant channel adjustments, zones of deposition and erosion, or necessary maintenance that had been undertaken subsequent to installation.

If pre-project monitoring data are unavailable it might be necessary to synthesize data for the channel prior to construction of the project using a reference reach with matching characteristics. If this is required, qualitative and quantitative measurements performed in the reconnaissance survey can be used to help assess the response of the channel to the scheme.

4.2.4 Geomorphic Evaluation



The geomorphological evaluation is the last stage of the PPA procedure. This evaluation allows the geomorphological dynamics of the reach to be compared to channel form, distinguished in the performance audit and compliance audit, respectively. This provides an opportunity to determine important links between form and process, the results of which can be placed in a watershed-context to provide an overall geomorphic appraisal.

Conclusions can be made regarding whether the scheme has been successful both in its installation (compliance audit) and whether it is performing as expected (performance audit). These findings can be made with reference to two scales. The first is whether scheme has achieved its short-term objectives. This is with respect to its current stability within its surrounding environment and whether it is performing as planned. The second set of conclusions can be made with regard to its longer-term sustainability. This requires a longer-term outlook of the project viewing the scheme as an integral part of the interconnecting river system. This needs an assessment to made of the scheme which focuses on how resilient the scheme will be to normal environmental perturbations over a longer time period and thus inherently makes judgements on the project's overall sustainability (Brookes and Shields, 1996b).

4.3 Regional Sediment Appraisal Methodology

4.3.1 Introduction

The regional sediment appraisal method has been developed from the geomorphic post-project appraisal procedure outlined in section 4.2. However, the revised procedure also draws on other techniques such as the watershed baseline survey and fluvial audit (Environment Agency, 1998b) where appropriate. The regional sediment appraisal method is designed to make maximum use of available data and minimise the amount of additional fieldwork performed to supplement the existing information to the minimum necessary to gain a comprehensive understanding of regional sediment issues. However, as the results of the literature review, questionnaire and surveys reported in sections 2 and 3 demonstrate, in many projects regional sediment data are either insufficient or non-existent. Hence, the appraisal includes two analytical approaches to regional sediment survey (Figures 10 and 11). Selection of approach to be used depends on the availability of data on sediment parameters and dynamics around the project reach and in the wider watershed. If, data are insufficient or non-existent then *Approach 1* should be followed. Where regional sediment data already exist, the high cost and resource commitment associated with intensive fieldwork can be avoided under *Approach 2*. The three stages of the sediment appraisal methodology (including specifications for essential fieldwork such as morphological surveys, sediment sampling and analysis in *Approach 1*) are outlined in sections 4.3.2-4.3.4.

4.3.2 Regional Sediment Survey

The Regional Sediment Survey is the first stage of the regional sediment appraisal procedure. Initially, a desk study is performed to gather background information and determine whether the available data are sufficient to support regional sediment appraisal. Useful sources of background information include documents related to the scheme, descriptions of the watershed and any academic papers that have previously been written. The primary product of the desk study is a written account and time chart of historical watershed changes and potentially destabilising phenomena. This identifies historic and recent changes within the watershed that might have had direct, or indirect, impacts on the fluvial and sediment transfer systems. This information can be used to identify causal links between historic activities and changes in the watershed and on-going sediment dynamics and morphological changes in the

fluvial system and so establish a general framework within which to appraise sediment issues related specifically to the project.

In *Approach 1*, when little or no archival data on sediment characteristics and dynamics are available, an extended stream reconnaissance survey is performed to form the basis for assessment of the regional sediment issues specific to the project. The reconnaissance survey centres on the project reach but it is extends far enough upstream and downstream to ensure that any effects of the project's installation are fully represented in the results. In the case of large schemes or small watersheds, this may require reconnaissance of the whole system. In large watersheds, reconnaissance is unlikely to encompass the entire drainage network, but will cover substantial reaches around the project and may encompass an entire sub-watershed.

In *Approach 1*, a detailed reconnaissance survey is undertaken. This will include: surveyed cross-sections and bed slopes in key reaches and at strategic locations; identifying grade and planform controls such as structures and geological outcrops; noting existing sediment control measures; classification of channel morphology and reach-scale stability status; and sampling the composition of the bed (surface and substrate), bars and banks at selected locations. The reconnaissance survey should aim to distinguish any current Potentially Destabilising Phenomena (PDPs) – that is factors that might be currently contributing to channel instability, erosion and deposition (Environment Agency, 1998b). Any current PDPs are then added to the historic PDPs identified in the desk study to produce an overview of past and present watershed and system effects on channel stability that could explain its evolution and instability. This is vital in order to identify and isolate sediment impacts and morphological responses that are attributable to the project, rather than the pre-existing effects of other PDPs.

In *Approach 2* the extended reconnaissance survey is unnecessary because the necessary watershed and reach-scale data and assessments have already been undertaken (ideally in the design phase of the project). Despite this, a basic reconnaissance of the fluvial system (or sub-system in a large watershed) should still be performed to familiarise the appraiser with the channel and support assessment of post-construction responses. This survey should assess the watershed and fluvial system in the context of sediment dynamics, channel morphology and morphological response together with measurements of cross-sectional geometry, reach slope, and surface, substrate, bar and bank material composition at a few selected, strategic locations.

4.3.3 Project Scale Sediment Assessment

The project scale assessment is split into the compliance and performance audits. The method is the same regardless of whether the Regional Sediment Survey employed *Approach 1* or *2*. The compliance assessment establishes whether the scheme has been constructed as planned. Design plans and drawings are compared to the project 'as built' to identify any intentional or incidental departures from the intended design. The audit makes use of 'as built' plans and specifications where these exist. Where 'as built' plans are unavailable, a survey of the scheme immediately following construction must be undertaken to assess the compliance. Unfortunately, it is seldom possible to gain access immediately after construction and if there has been a delay between completion and the post-construction audit then efforts should be made to identify whether any events (floods, low flows, vandalism etc.) have impacted the project have occurred during the interim.

The performance audit extends beyond the project reach to include the reaches immediately up and downstream to investigate whether sediment and morphological changes have occurred since the scheme was constructed. The audit may be performed at one or two levels, depending on the resources available to support the Regional Sediment Appraisal effort. If resources are limited, the first level audit relies on field monitoring (and/or visual identification) and evaluation of zones of erosion and deposition within the project and adjacent reaches. If sufficient resources exist, the second level audit employs a quantitative channel survey and numerical channel stability analysis (Soar, 2000; Soar *et al.*, 2001).

In the first level audit the results of any pre and post-project monitoring are supplemented by a reconnaissance survey to map spatial and temporal patterns of erosion, deposition, bar migration and lateral shifting of the channel at reach-scale. The morphological responses to the project so identified are then evaluated in conjunction with the flow record to determine whether major events may be responsible for some or all of the observed morphological response. The insights gained from monitoring and evaluation are then used to assess whether morphological response is characterised by local changes, reach-scale adjustments or wider-scale instability associated with disruption of the regional scale sediment system.

The second level audit employs a quantitative sediment impact assessment to characterise sediment dynamics through the project reach after implemented. The sediment impact assessment is used to:

1. "validate the efficacy of the engineered or restored channel geometry;
2. identify flows which may cause aggradation or degradation over the short-term;
3. recommend fine tuning of the project design to ensure that dynamic stability will be ensured over the medium to long-term."

(from Soar *et al.*, 2001)

The output product of the second level audit is the Capacity-Supply Ratio (CSR). If the CSR equals unity this indicates balance between sediment transport capacity in the project reach and the supply from upstream. In practice, a CSR within =/- 10% of unity, suggests dynamic stability and the establishment of morphological features within the project reach (Soar *et al.*, 2001).

The results of the project scale sediment assessment (first or second level) define the extent to which the project 'as built' has disturbed sediment continuity between the project reach and the reaches immediately up and downstream. To widen the scope of the appraisal to the system scale, the final stage in the method is to consider the results of regional sediment assessment a together with those of the project scale assessment within the wider drainage network and watershed. This is achieved in the Regional Scale Appraisal.

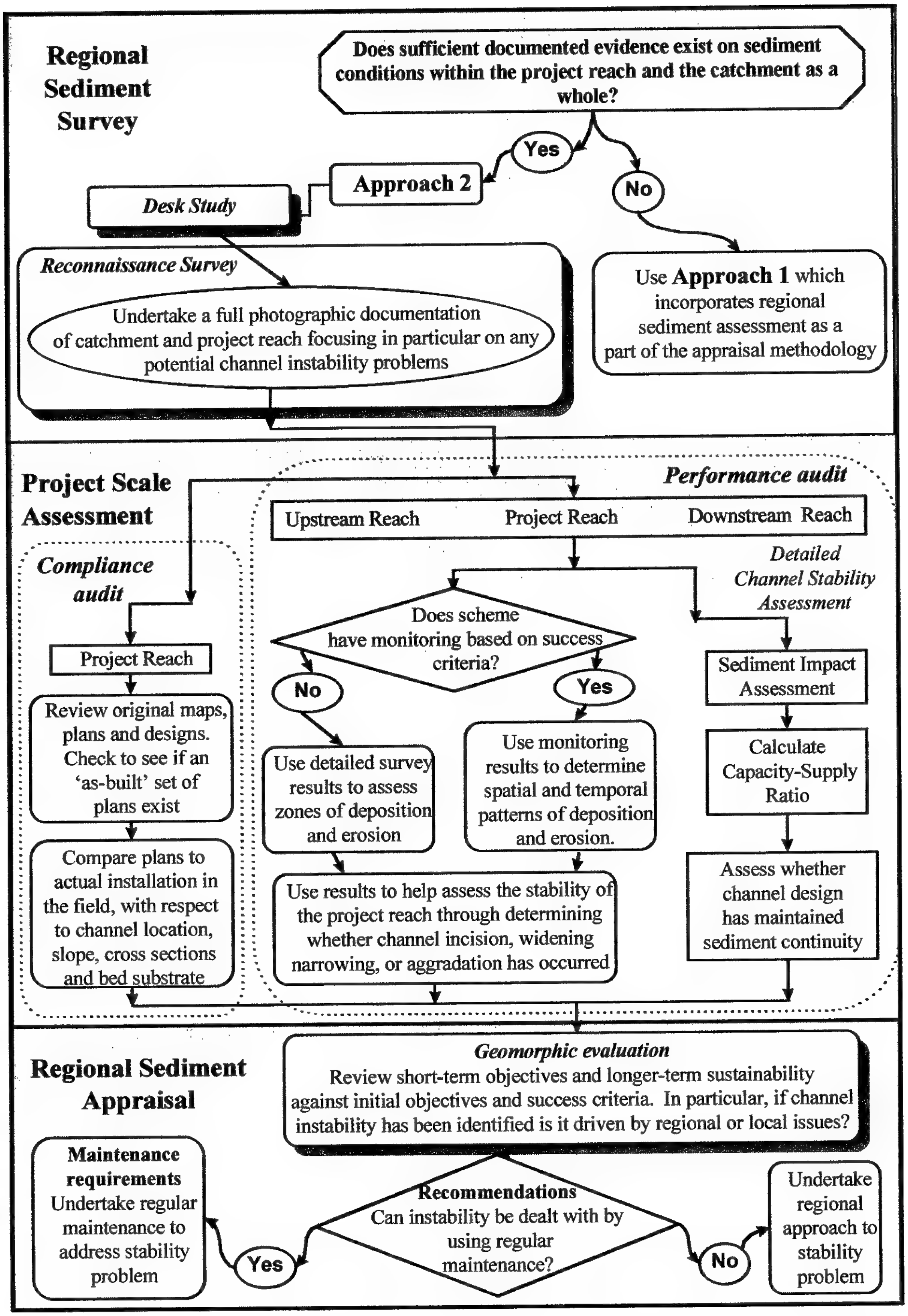


Figure 10: Regional Sediment Appraisal Methodology: Approach Selection and Approach 2

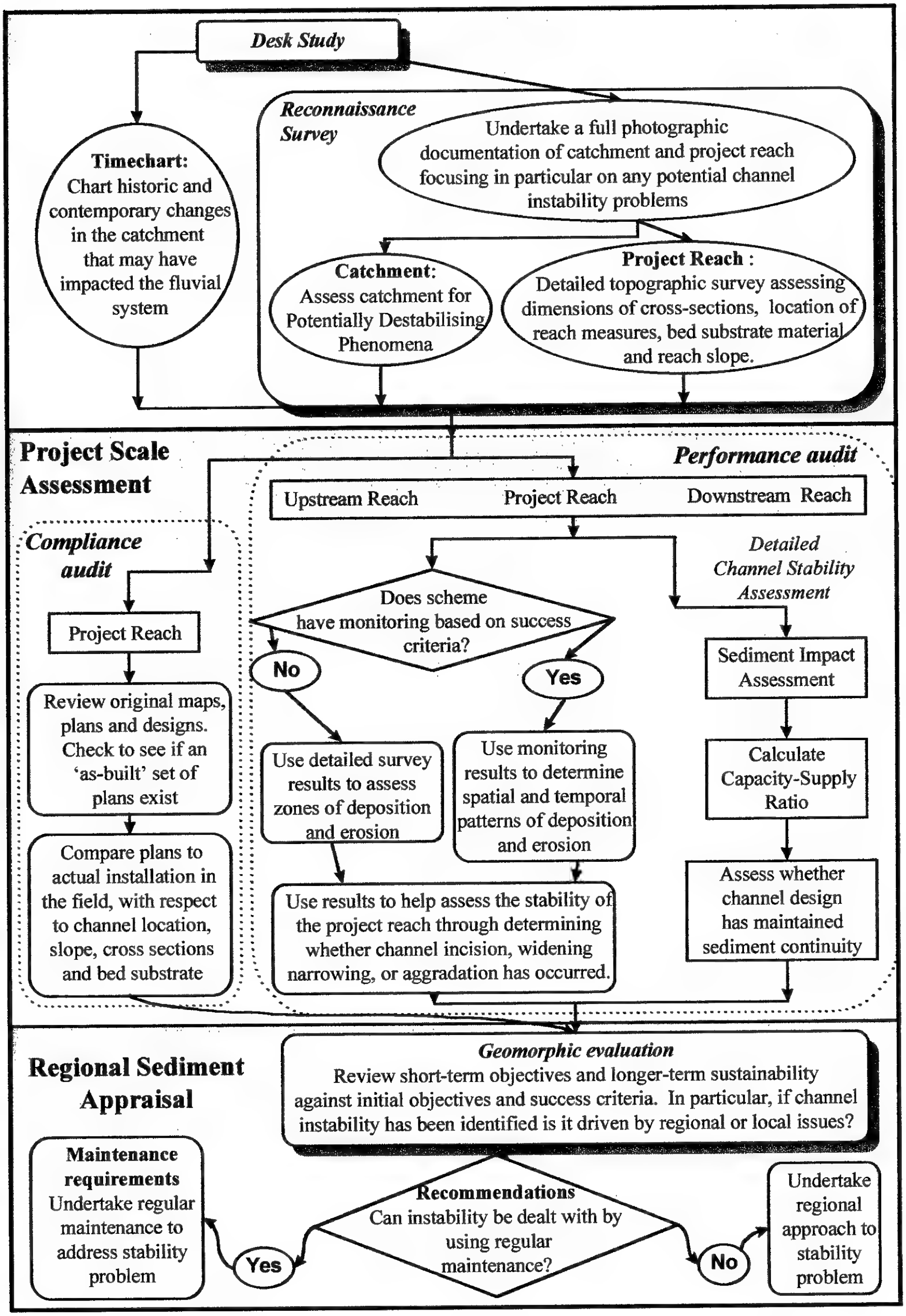


Figure 11: Regional Sediment Appraisal Methodology – Approach 1

4.3.4 Regional Sediment Appraisal

The final stage of the appraisal method evaluates the results of the compliance and performance audits with reference to the regional sediment assessment. The first aim is to re-evaluate the outcome of the project scale sediment assessment within the wider scope of the regional sediment assessment and determine whether any disruption of the sediment transfer system caused by the project is of local, reach or system-wide significance. The second aim of the regional sediment appraisal is to identify whether causal links exist between any channel instability found either in the vicinity of the project or the wider system, and sediment imbalance driven by disruption of the regional sediment system by the project. In establishing causal links, consideration must always be given to PDPs that pre-date the project as post-project morphological response may in fact be part of longterm evolution of the system to historical changes in watershed or drainage network management.

If success criteria were defined during project feasibility and design phases, the Appraisal should make reference to these criteria in judging the success of the scheme. The findings of the regional sediment appraisal are then used to support decision making on appropriate maintenance, adaptive management, further capital works or even rehabilitation of the project as necessary to achieve and sustain success. This is especially important where a scheme has met its short-term objectives but questions remain concerning its longer–term sustainability. Where the Project scale sediment assessment reveals only problems driven by local processes these may be addressed through a targeted maintenance program. Where project-related problems are identified in adjacent reaches, adaptive management or further capital works may be necessary to deal with them: it is doubtful that maintenance alone will provide a long-term solution. In the most serious cases, where the regional sediment system has been significantly disrupted leading to widespread morphological response, it may be necessary to redesign the project or rehabilitate the entire fluvial system: maintenance and management would not be sufficient to adequately deal with such a system-wide problem.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This document provides a brief outline of contemporary practice in regional sediment management through a review of various literature sources in addition to documented correspondence with key practitioners around the world. Responses to an initial enquiry, followed by a questionnaire provided the basis for a broad assessment of current practice. The results revealed that Regional sediment management appears to be a fairly recent concept in river management. Historically, schemes have adopted a reach focus neglecting wider watershed issues and this has led to a series of well documented failures (Frissell and Nawa, 1992; O'Neill and Fitch, 1992; Beschta *et al.*, 1994; Miles, 1998).

During the 1990s a number of watershed based approaches evolved including ntable examples from Europe and Australia (Brierley and Fryirs, 2000; Environment Agency, 1998b; Petts and Amoros, 1996a). The focus on many of the methods has the need to understand the watershed

scale system before designing flood control or restoration schemes. In addition to these approaches has been the development of reach based design methodologies that have focused on the understanding the sediment continuum in designing a variety of river management schemes (Soar, 2000; Soar *et al.*, 2001). Through adopting these types of approaches there is an increased probability that the schemes will be sustainable with respect to the regional sediment system.

The review of documented literature suggested that projects that have had considered the movement of sediment in their design have mostly been either demonstration projects, large interdisciplinary projects or schemes that have had a high degree of academic involvement. Many of the journal papers reviewed did not state explicitly how sediment issues were dealt with in the planning and design stages. It was therefore difficult to determine the seriousness with which regional sediment issues were considered. In any case, the outcome was that in many cases the sediment budget was not considered a high priority in the engineering analysis and design. In the literature search for schemes that did consider regional sediment issues, were found to be mostly concerned with either restoration or rehabilitation of the fluvial system. In contrast, few flood control projects considered regional sediment continuity.

Post-project monitoring and appraisals are seldom undertaken, even in restoration and rehabilitation schemes. This is regrettable as both are integral to the application and further development of the restoration process. In practice, it is difficult to assess the success of schemes and learn from experience unless monitoring and appraisal are undertaken. The future of river engineering rests on implementation of appropriate strategies to ensure that projects are sustainable in the long-term and this absolutely requires post-project appraisal and adaptive management as watershed and drainage networks evolve through time (Ladson *et al.*, 1999; Stewardson *et al.*, 1999). To ensure that a project is sustainable it is essential to determine the intensity, extent and duration of disruption caused to the regional sediment transfer system. This relies on agencies setting aside sufficient funds in the project budget for a Regional Sediment Appraisal to be performed. Unfortunately, the budget for most schemes only extends to the installation phase (Kondolf and Micheli, 1995). A draft method for conducting such Regional Sediment Appraisal is presented here and, after further testing and development, this could form the basis for a standardised approach.

5.2 Recommendations

5.2.1 General recommendations

It is recommended that future schemes adopt a watershed scale approach to enable engineered or restored reaches to be designed appropriately within the sediment continuum. The need to understand complex watershed scale processes in the development of channel morphology is of paramount importance when designing a project. Several approaches have been developed to understand how geomorphic processes define how the physical template of a river system upon which the interaction of a wide range of the biophysical processes occur. These include both the fluvial hydrosystem concept (Petts and Amoros, 1996c) and the river styles approach

(Brierley and Fryirs, 2000). In addition, methods, such as the fluvial audit (Environment Agency, 1998b) have been developed to provide an assessment of the sediment budget in a previously identified problem reach within the context of the wider watershed system. This provides a technique that can be used to locate an appropriate reach for any restoration work. More detailed reach-scale techniques have also incorporated sediment budget into their design methodologies (Soar, 2000; Soar *et al.*, 2001). It is recommended that a combination of these approaches be used and developed further to enable schemes to be designed in the appropriate location and with a stable morphology within their environmental setting. It is also important that these methods be incorporated into current design guidelines in various countries such as the Federal Interagency Stream Restoration Working Group guidelines (FISRWG, 1998) in the USA, or the Rehabilitation Manual for Australian Streams (Rutherfurd *et al.*, 2000) in Australia (which included the River Styles approach).

5.2.2 Further work

Key recommendations for further work have evolved from this review. These are outlined below:

- To use, test, and further refine, watershed based approaches such as the fluvial hydrosystem approach, the river styles methodology and the fluvial audit in determining the most appropriate siting for restoration schemes.
- To expand the use of watershed based approaches in the design phases of river engineering schemes. This should help identify any potential instability problems prior to the installation of a scheme.
- To develop a method that would provide a semi-quantitative sediment budget of a fluvial system. The technique should aim to investigate where wash load becomes bedload within the watershed system. This could be used in conjunction with watershed based approaches, such as the fluvial audit, to provide a broad assessment of the watershed scale sediment dynamics in the design phase of scheme.
- To test, and refine, the Channel Restoration Design Methodology for Meandering Rivers (Soar, 2000).
- To test, and refine, the Regional Sediment Appraisal methodology for assessing sediment issues in restored and engineered fluvial systems.

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APPENDICES

Appendix 1: List of Correspondents

- Giuseppe Baldo, Italian Centre for River Restoration, Italy
- Helmut Habersack, University of Agricultural Sciences, Vienna, Austria
- Hans Ole Hansen, Danish Centre for River Restoration, Denmark
- Karen Hills, WS Atkins, UK
- Malcolm Newson, University of Newcastle, UK
- Arthur Parola, University of Louisville, Kentucky, USA
- Herve Piégay, University of Lyon, France.
- John Pitlick, University of Colorado, Colorado, USA
- David Sear, University of Southampton, UK
- Doug Shields Jnr, National Sedimentation Laboratory, Mississippi, USA
- Maciej Zalewski, University of Lodz, Poland

Appendix 2

Questionnaire on the 'Geomorphic approach to Regional Sediment Management in Engineered and Restored Fluvial Systems'

Note: Please could you tick the appropriate boxes or provide an approximate answer where requested. Thanks.

OF THE RESTORATION/FLOOD DEFENCE SCHEMES THAT YOU HAVE BEEN INVOLVED WITH, OR ARE AWARE OF, WHAT PERCENTAGE WOULD YOU SAY HAVE CONSIDERED THE MOVEMENT OF SEDIMENT IN THE PLANNING OF THE SCHEME.

Percentage	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
(please tick box)										

1 Of those schemes that have considered sediment transfer at what stage in the design process was sediment movement considered and how was it incorporated into the design (please provide an answer for the 3 most well documented schemes that you are aware of)?

Name of River	What stage was sediment considered in the design process?	How was the sediment movement accounted for in the design of the project (please provide details)?
1)		
2)		
3)		

2 Of those schemes that have considered sediment transfer at what scale has this been examined at:

SCALE	What percent?	Please could you expand the answer with more detail
Project reach	%	
Project Reach as well as immediately up and downstream	%	
Watershed Perspective	%	
Other (please define)	%	

1 What methods have been used to determine sediment transfer rates?

METHOD	Please expand on what techniques have been used and why they were considered to be the most appropriate
Empirical	
Modelling	
Sediment Transport equations	
Other (please name)	

2 Of the projects that you are aware of what percentage of schemes have either had a) Monitoring or b) Appraisals undertaken after the scheme was installed (please tick box)?

Percentage	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
Monitoring										
Appraisals										

3 If monitoring was undertaken what have this focused on?

	Please expand on how frequently the measures were analysed and what the surveys actually encompassed
Cross-section analysis	
Substrate composition	
Stability of rehabilitation measures	
Other (please specify)	

4 If appraisals have been undertaken……

Question	Success rate	Percentage in each category	Please expand on why the schemes were considered a success or failure
a) Were the schemes considered to be largely successful?	Degree of success		
	Complete		
	High degree		
	Some success but also some failures		
	Partial		
	Total Failure		
	Please could you expand your answer to provide us with a picture of contemporary practice		
b) Were the appraisals based on the results of a monitoring survey?			
c) Were the appraisals based on success criteria defined prior to the schemes installation?			
d) Were there any large scale problems associated with channel stability after the installation?			

If there have any further comments on schemes that you have dealt with or the project in general please add them in the box below.

Additional Comments:

Many thanks for completing this questionnaire we will of course provide you with a copy of the completed report later this year. If you would like your views to remain confidential then please could you tick the box provided.